

Kernel Attacks through User-Mode Callbacks

Tarjei Mandt
SyScan'11 Taipei

Who am I

- **Security Researcher at Norman**
 - Malware Detection Team (MDT)
- **Interests**
 - Vulnerability research
 - Operating system internals
- **Past Work**
 - Kernel Pool Exploitation on Windows 7
 - Mitigating NULL Pointer Exploitation on Windows

About this Talk

- **Several vulnerability classes related to windows hooks and user-mode callbacks**
 - Null pointer dereferences
 - Use-after-frees
- **Resulted in 44 patched privilege escalation vulnerabilities in MS11-034 and MS11-054**
 - Several unannounced vulnerabilities were also addressed as part of the variant discovery process
- **Requires understanding of several mechanisms specific to NT and win32k**

Agenda

- **Introduction**
- **Win32k**
 - Window Manager
 - User-Mode Callbacks
- **Vulnerabilities**
- **Exploitability**
- **Mitigations**
- **Conclusion**

Introduction

Win32k and User-Mode Callbacks

Win32k

- **The Windows GUI subsystem was traditionally implemented in user-mode**
 - Used a client-server process model
- **In NT 4.0, a large part of the server component (in CSRSS) was moved to kernel-mode**
 - Introduced Win32k.sys
- **Today, Win32k manages both the Window Manager (USER) and the Graphics Device Interface (GDI)**

User-Mode Callbacks

- **Allows win32k to make calls back into user-mode and operate on user-mode data**
 - Invoke application defined hooks
 - Provide event notifications
 - Read and set properties in user-mode structures
- **Implemented in the NT executive**
 - nt!KeUserModeCallback
 - Works like a reverse system call

Win32k vs. User-Mode Callbacks

- **Win32k uses a global locking design in creating a thread-safe environment**
 - Presumably remnants of the old subsystem design
- **Callbacks “interrupt” kernel execution and allow win32k structures and object properties to be modified**
- **Insufficient checks or validation may result in numerous vulnerabilities**
 - Use-after-frees
 - NULL pointer dereferences
 - ++

Previous Work

- **Mxatone - Analyzing local privilege escalations in win32k (Uninformed vol.10)**
 - Insufficient validation of data returned from user-mode callbacks
- **Win32k Window Creation Vulnerabilities**
 - CVE-2010-0484 (MS10-032)
 - Window parent not revalidated after callbacks
 - CVE-2010-1897 (MS10-048)
 - Pseudo handle provided in callback not sufficiently validated
- **Stefan Esser - State of the Art Post Exploitation in Hardened PHP Environments (Black Hat USA 2009)**
 - Interruption vulnerabilities

Goals

- Show how user-mode callbacks without very stringent checks may introduce several subtle vulnerabilities
- Show how such vulnerabilities may be exploited using pool and kernel heap manipulation
- Propose a method to generically mitigate exploitability of NULL pointer dereference vulnerabilities

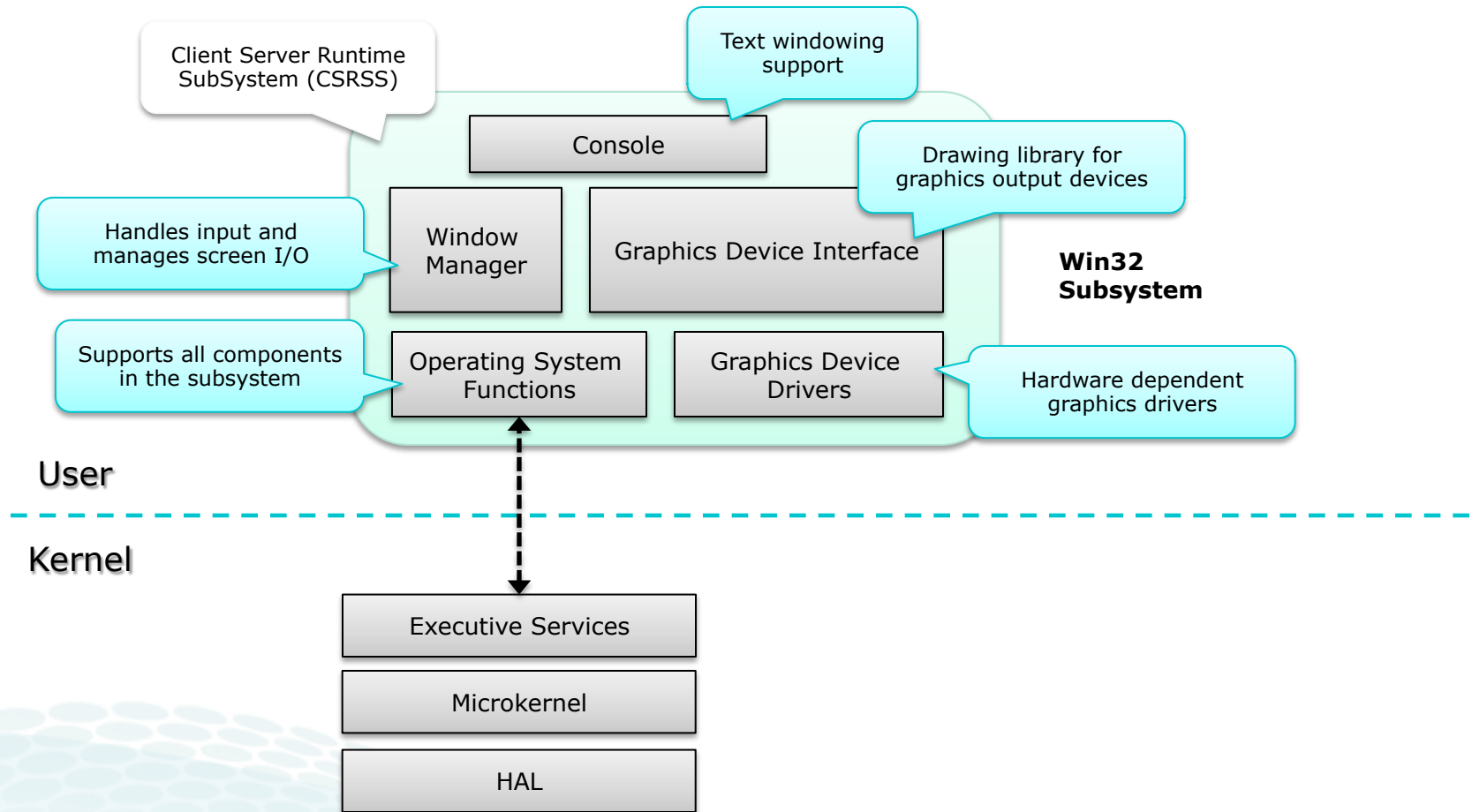
Win32k

Architecture and Design

Windows NT 3.51

- **Modified microkernel design**
 - File systems, network protocols, IPC, and drivers are implemented in kernel mode
- **Followed a more pure microkernel approach in its implementation of the GUI subsystem**
 - Window Manager and GDI implemented in the Client-Server Runtime SubSystem (CSRSS)
- **Optimized for performance**
 - Shared memory design
 - Paired threads between client and server (FastLPC)

Windows NT 3.51 Win32 Subsystem



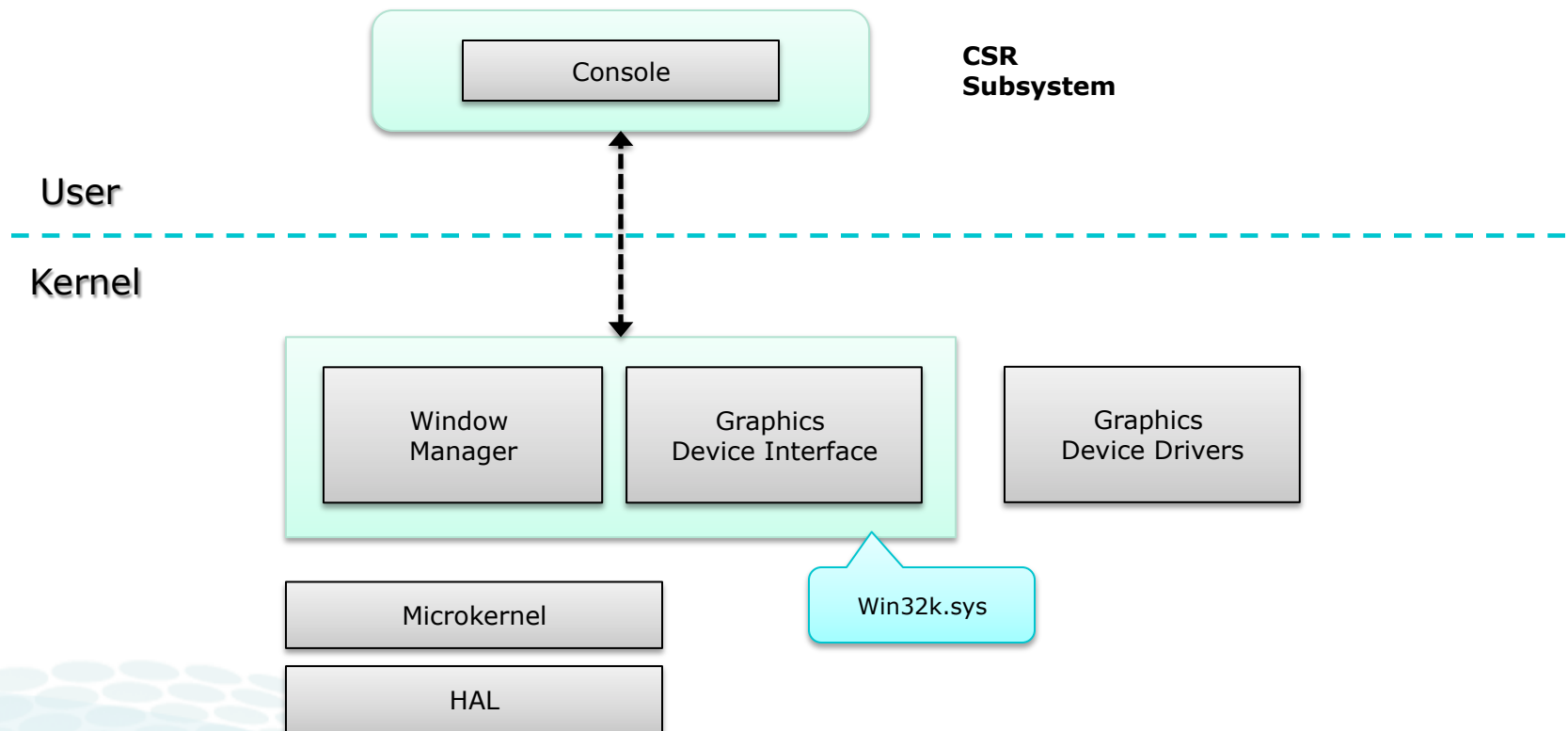
Drawbacks of the NT 3.51 Design

- **Graphics and windowing subsystem have a very high rate of interaction with hardware**
 - Video drivers, mouse, keyboard, etc.
- **Client-server interaction involves excessive thread and context switching**
 - Greatly affects graphics rendering performance
- **High memory requirements**
 - Uses 64K shared memory buffer to accumulate and pass parameters between the client and server

Windows NT 4.0

- **Moved the Window Manager, GDI and graphics device drivers to kernel-mode**
 - Introduced win32k.sys
- **Eliminated the need for shared buffers and paired threads**
 - Resulted in fewer thread and context switches
 - Reduced memory requirements
- **Some old performance tricks were still maintained**
 - E.g. caching of kernel structures in the user mode portion of the client's address space

Win32k.sys in Windows NT 4.0



Win32k

- **Kernel component of the Win32 subsystem**
- **Implements the kernel side of**
 - Window Manager (USER)
 - Graphics Device Interface (GDI)
- **Provides thunks to DirectX interfaces**
- **Has it's own system call table**
 - More than 800 entries on Windows 7
 - win32k!W32pServiceTable

Window Manager (USER)

- **Several responsibilities**
 - Controls window displays
 - Manages screen output
 - Collects input from keyboard, mouse, etc.
 - Calls application-defined hooks
 - Passes user messages to applications
 - Manages user objects
- **The component this talk will focus on**

Graphics Device Interface (GDI)

- **Manages the graphics output and rendering**
 - Library of functions for graphics output devices
 - Includes functions for line, text, and figure drawing and for graphics manipulation
 - Manages GDI objects such as brushes, pens, DCs, paths, regions, etc.
 - Provides APIs for video/print drivers
- **Slow compared to Direct2D/DirectWrite**
 - Will probably be replaced at some point

Window Manager

User Objects and Thread Safety

User Objects

- **All user handles for entities such as windows and cursors are backed by their own object**
 - Allocated in `win32k!HMAAllocateObject`
- **Each object type is defined by a unique structure**
 - `win32k!tagWND`
 - `win32k!tagCURSOR`
- **User objects are indexed into a dedicated handle table maintained by win32k**
- **Handle values are translated into object pointers using the handle manager validation APIs**
 - `win32k!HMValidateHandle(..)`

User Object Header

- Every user object starts with a HEAD structure
- `kd> dt win32k!_HEAD`
 - `+0x000 h` : `Ptr32 Void` // handle value
 - `+0x004 cLockObj` : `Uint4B` // lock count
- **The lock count tracks object use**
 - An object is freed when the lock count reaches zero
- **Additional fields are defined if the object is owned by a thread or process, or associated with a desktop**
 - `win32k!_THRDESKHEAD`
 - `win32k!_PROCDESKHEAD`

User Handle Table

- All user objects are indexed into a per-session handle table
 - Initialized in win32k!Win32UserInitialize
- Pointer to the user handle table is stored in the win32k!tagSHAREDINFO structure
 - user32!gSharedInfo (Win 7) or win32k!gSharedInfo
- **kd> dt win32k!tagSHAREDINFO**
 - +0x000 psi : Ptr32 tagSERVERINFO
 - +0x004 aheList : Ptr32 _HANDLEENTRY
 - +0x008 HeEntrySize : Uint4B
 - +0x00c pDisplInfo : Ptr32 tagDISPLAYINFO
 - +0x010 ulSharedDelta : Uint4B

User Handle Table Entries

- Each entry in the user handle table is represented by a **HANDLEENTRY** structure
- **kd> dt win32k!_HANDLEENTRY**
 - +0x000 phead : Ptr32 _HEAD
 - +0x004 pOwner : Ptr32 Void
 - +0x008 bType : Uchar
 - +0x009 bFlags : Uchar
 - +0x00a wUniq : Uint2B
- **Holds pointers to the object, its owner, type, flags, and a unique seed for the handle values**
 - $\text{handle} = \text{handle_table_index} \mid (\text{wUniq} \ll 0x10)$
 - *wUniq* is incremented on object free

User Handle Table Entries

object	owner	bType	bFlags	wUniq
0	0	0	0	0
ff9d1d28	0	c	0	1
ffbbd498	ffb09678	1	40	1
ffb658f0	ffbbc958	3	0	1
ff650618	ffb09678	1	0	1
ffb64918	ffbbc958	3	0	1

Pointer to object
in kernel memory

Pointer to owner
(THREADINFO or
PROCESSINFO)

Object type (e.g.
window, cursor,
menu, etc.)

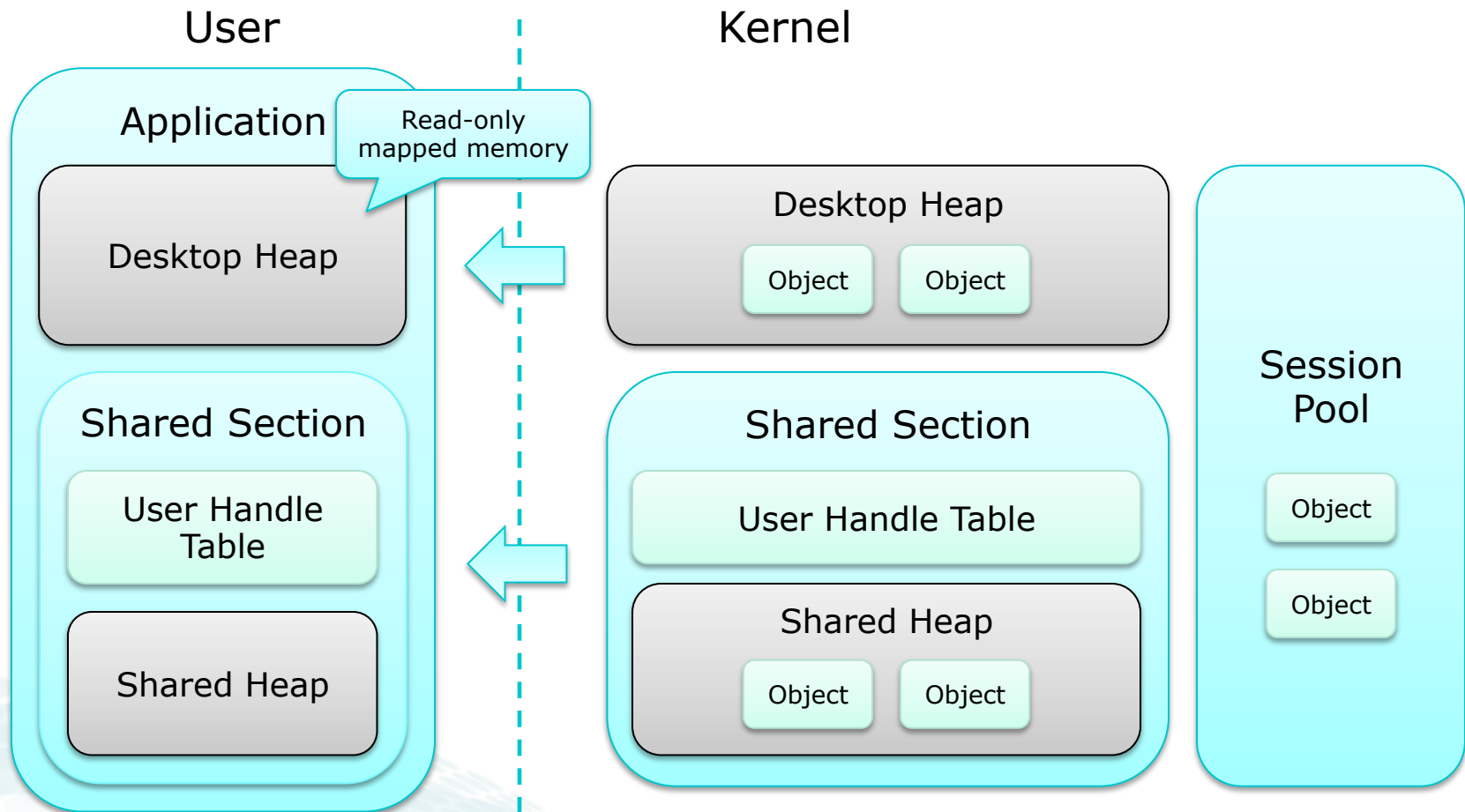
Object flags (e.g.
being destroyed)

Unique
counter

User Objects In Memory

- User objects are stored in the *session pool*, the *desktop heap* or the *shared heap*
- The desktop heap and shared heap are read-only mapped into user address space
 - Used to avoid kernel transitions
- **Objects associated with a particular desktop are stored on the desktop heap**
- **Remaining objects are stored in the shared heap or the session pool**

Handle Table & Objects In Memory



Shared Section User Mapping

- **The shared section is mapped into a GUI process upon initializing the client Win32 subsystem**
 - Essentially means loading user32.dll
 - Mapping itself is performed by CSRSS in calling NtUserProcessConnect (InitMapSharedSection)
- **The user handle table, at the base of the shared section, can be obtained in at least two ways**
 - From user32!gSharedInfo (exported on Windows 7)
 - From the connection information buffer returned by **CsrClientConnectToServer** upon specifying **USERSRV_SEVERDLL_INDEX (3)**

Handle Table From User-Mode

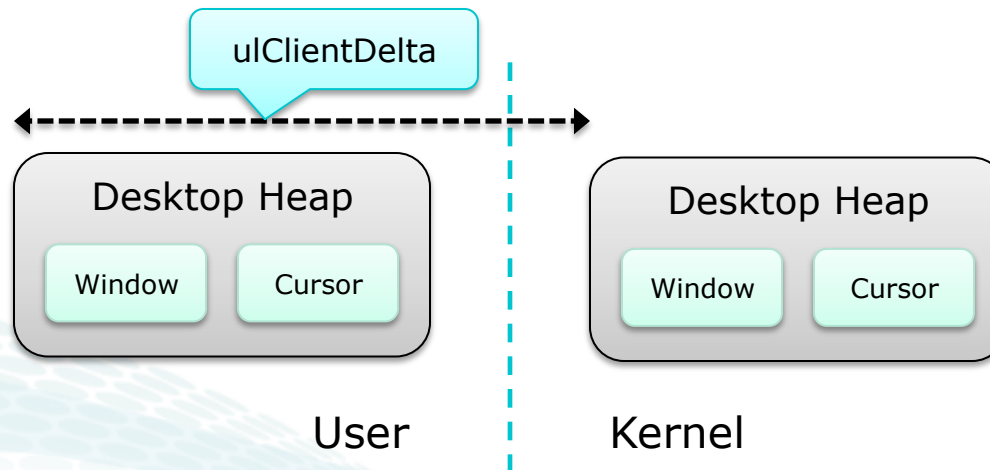
```
C:\WINDOWS\system32\cmd.exe - sharedinfo.exe
*****
Index      Handle      Object      Owner      Type
*****
[0000]      10000      0           0           0 <Free>
[0001]      10001      bc5d1b48    0           c <Monitor>
[0002]      10002      e1a12698    e1a13008    1 <Window>
[0003]      10003      e15a91f8    e15ad650    3 <Icon/Cursor>
[0004]      10004      bc6006e8    e1a13008    1 <Window>
[0005]      10005      e163c670    e15ad650    3 <Icon/Cursor>
[0006]      10006      bc600818    e1a13008    1 <Window>
[0007]      10007      e15aee80    e15ad650    3 <Icon/Cursor>
[0008]      10008      bc600940    e1a13008    1 <Window>
[0009]      10009      e15aee20    e15ad650    3 <Icon/Cursor>
[000a]      1000a      bc600a88    e1a13008    1 <Window>
[000b]      1000b      e15adb80    e15ad650    3 <Icon/Cursor>
[000c]      1000c      bc6206e8    e1a13008    1 <Window>
[000d]      1000d      e17c2658    e15ad650    3 <Icon/Cursor>
[000e]      1000e      bc620818    e1a13008    1 <Window>
[000f]      1000f      e17c1610    e15ad650    3 <Icon/Cursor>
[0010]      10010      bc620940    e1a13008    1 <Window>
[0011]      10011      e17b22a8    e15ad650    3 <Icon/Cursor>
[0012]      10012      bc620a88    e1a13008    1 <Window>
[0013]      10013      e17d7e20    e15ad650    3 <Icon/Cursor>
[0014]      10014      bc6306e8    e1a13008    1 <Window>
[0015]      10015      e17d7dc0    e15ad650    3 <Icon/Cursor>
```

Desktop Heap User Mapping

- For each GUI thread, win32k maps the associated desktop heap into the user-mode process
 - Performed by win32k!MapDesktop
- Information on the desktop heap is stored in the desktop information structure
 - Holds the kernel address of the desktop heap
 - Accessible from user-mode
 - NtCurrentTeb()->Win32ClientInfo.pDeskInfo
- **kd> dt win32k!tagDESKTOPINFO**
 - +0x000 pvDesktopBase : Ptr32 Void
 - +0x004 pvDesktopLimit : Ptr32 Void

Kernel-Mode -> User-Mode Address

- **User-space address of desktop heap objects are computed using ulClientDelta**
 - `NtCurrentTeb()->Win32ClientInfo.ulClientDelta`
- **User-space address of shared heap objects are computed using ulSharedDelta**
 - Defined in `win32k!tagSHAREDINFO`



User Object From User-Mode

```
C:\WINDOWS\system32\cmd.exe
C:\Documents and Settings\vmware\Desktop>sharedinfo.exe 20096 a4
[*] Dumping object data for handle: 20096
0000h: 00020096 00000001 e183f720 818d6238 ..... 8b..
0010h: bbe8c818 00000000 80000300 c0000800 .....
0020h: 54009945 00000000 00000000 00000000 E..T.....
0030h: 00000000 bbe8c768 00000000 00000000 .....h.....
0040h: 00000000 00000004 0000017c 00000026 .....|...&...
0050h: 00000000 00000004 0000017c 00000026 .....|...&...
0060h: 773e208b bbe88328 00000000 bbe8c700 .>w<.....
0070h: 00000000 00000000 00000000 00000000 .....
0080h: 00000000 00000000 00000000 00000004 .....
0090h: 00000000 00000000 00000000 0009e508 .....
C:\Documents and Settings\vmware\Desktop>
```


User Object Types

- On Windows 7, there are 21 different user object types (22 including the 'free' type)
 - Includes 'touch' and 'gesture' objects
- Information on each type is stored in the handle type information table
 - win32k!ghti (undocumented structure)
 - Defines the destroy routines for each type
 - Defines target memory location (desktop/shared heap, session pool)

User Object Types #1

ID	TYPE	OWNER	MEMORY
0	Free		
1	Window	Thread	Desktop Heap / Session Pool *
2	Menu	Process	Desktop Heap
3	Cursor	Process	Session Pool
4	SetWindowPos	Thread	Session Pool
5	Hook	Thread	Desktop Heap
6	Clipboard Data		Session Pool
7	CallProcData	Process	Desktop Heap
8	Accelerator	Process	Session Pool
9	DDE Access	Thread	Session Pool
10	DDE Conversation	Thread	Session Pool

* Stored on the desktop heap if the window is associated with a desktop

User Object Types #2

ID	TYPE	OWNER	MEMORY
11	DDE Transaction	Thread	Session Pool
12	Monitor		Shared Heap
13	Keyboard Layout		Session Pool
14	Keyboard File		Session Pool
15	Event Hook	Thread	Session Pool
16	Timer		Session Pool
17	Input Context	Thread	Desktop Heap
18	Hid Data	Thread	Session Pool
19	Device Info		Session Pool
20 (Win 7)	Touch	Thread	Session Pool
21 (Win 7)	Gesture	Thread	Session Pool

User Critical Section

- **Unlike NT, the Window Manager does not exclusively lock each user object**
 - Implements a global lock per session
- **Each kernel routine that operates on win32k structures or objects must first acquire a lock on win32k!gpresUser**
 - Exclusive lock used if write operations are involved
 - Otherwise, shared lock is used
- **Clearly not designed to be multithreaded**
 - E.g. two separate applications in the same session cannot process their message queues simultaneously

Shared and Exclusive Locks

```
; Attributes: bp-based frame

; __stdcall NtUserCheckDesktopByThreadId(x)
_NtUserCheckDesktopByThreadId@4 proc near

var_4= dword ptr -4
arg_0= dword ptr 8

mov     edi, edi
push    ebp
mov     ebp, esp
push    ecx
push    esi
call    _EnterSharedCrit@0 ; EnterSharedCrit()
mov     esi, eax
call    ds:__imp__PsGetCurrentProcess@0 ; PsGetCurrentProcess()
push    eax
call    _IsProcessDwm@4 ; IsProcessDwm(x)
test    eax, eax
jnz     short loc_BF844222
```

Acquire shared lock

```
; Attributes: bp-based frame

; int __stdcall NtUserSwitchDesktop(HANDLE Handle, int)
_NtUserSwitchDesktop@8 proc near

var_10= byte ptr -10h
var_4= dword ptr -4
Handle= dword ptr 8
arg_4= dword ptr 0Ch

mov     edi, edi
push    ebp
mov     ebp, esp
sub     esp, 10h
push    esi
call    _UserEnterUserCritSec@0 ; UserEnterUserCritSec()
mov     eax, _gptiCurrent
xor     esi, esi
test    dword ptr [eax+00000000], 0
jz      short loc_BF8198
```

Acquire exclusive lock

User-Mode Callbacks

Kernel to User Interaction

User-Mode Callbacks

- In interacting with user-mode data, win32k is required to make calls back into user-mode
 - Lead to the concept of user-mode callbacks
- **Implemented in nt!KeUserModeCallback**
 - Works like a reverse system call
 - Previously researched by Ivanlef0u and mxatone, among others
- **Used extensively in user object handling**
 - Some user objects store data in user-mode

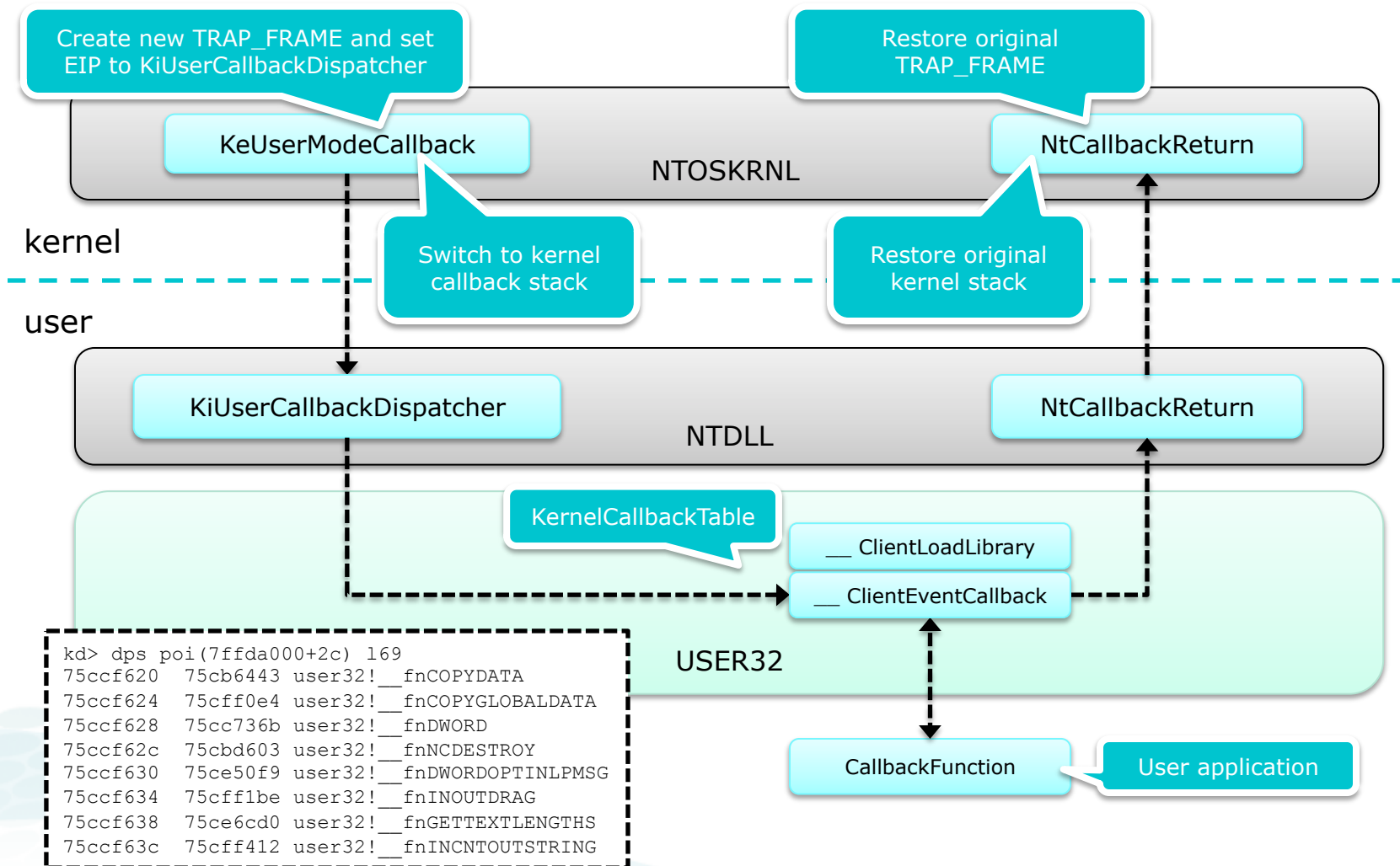
KeUserModeCallback

- **NTSTATUS KeUserModeCallback (**
 IN ULONG ApiNumber,
 IN PVOID InputBuffer,
 IN ULONG InputLength,
 OUT PVOID * OutputBuffer,
 IN PULONG OutputLength);
- ***ApiNumber* is an index into the user-mode callback function table**
 - Pointer copied to the Process Environment Block (PEB) during the initialization of USER32.dll in a process
- **kd> dt nt!_PEB KernelCallbackTable**
 - +0x02c KernelCallbackTable : Ptr32 Void

KeUserModeCallback Internals

- In a system call, a trap frame is stored on the kernel thread stack by KiSystemService or KiFastCallEntry
 - Used to save thread context and restore registers upon returning to user-mode
- **KeUserModeCallback creates a new trap frame (KTRAP_FRAME) before invoking KiServiceExit**
 - Sets EIP to ntdll!KiUserCallbackDispatcher
 - Replaces TrapFrame pointer of the current thread
- **Input buffer is copied to the user-mode stack**

KeUserModeCallback



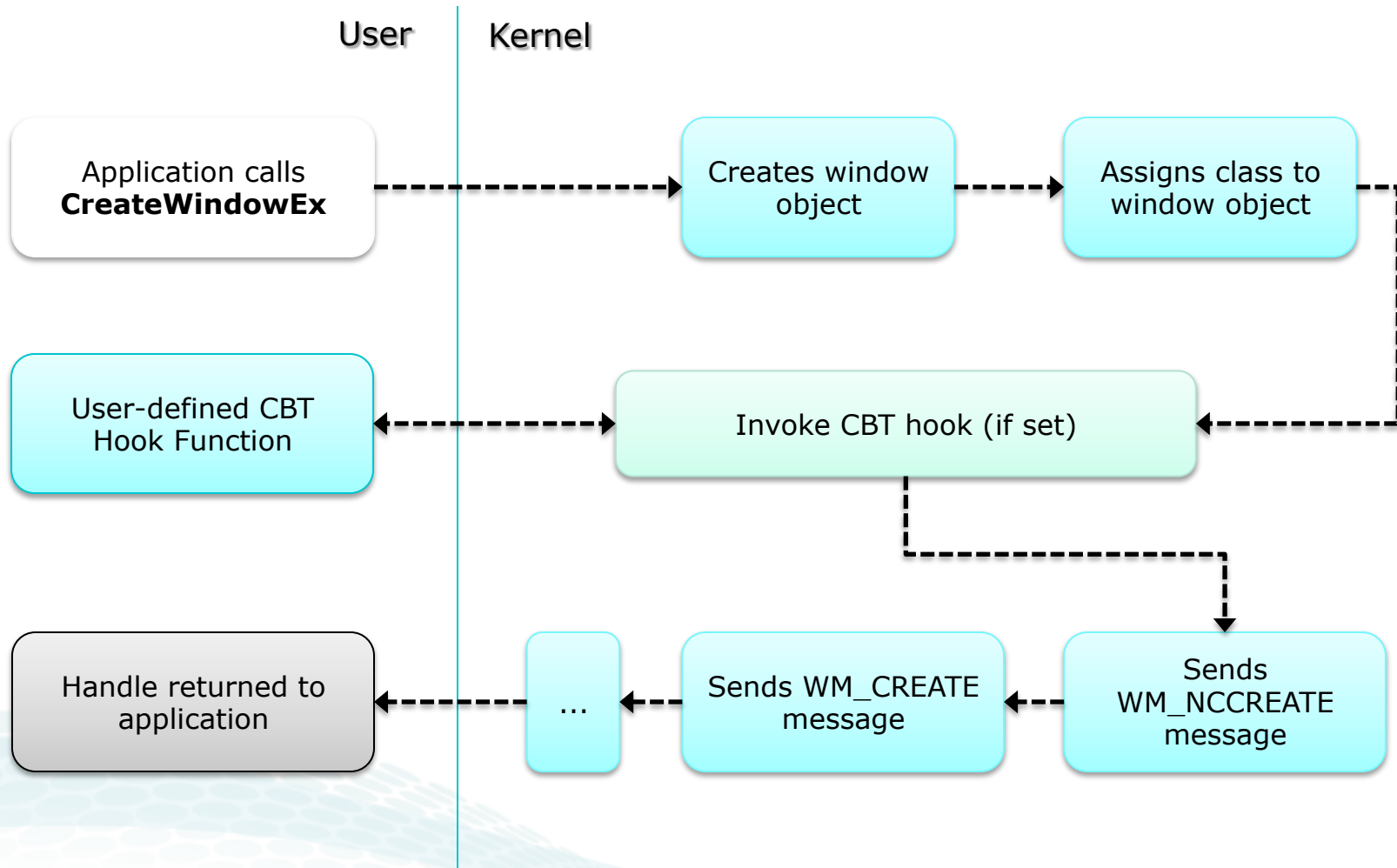
NtCallbackReturn

- **NTSTATUS NtCallbackReturn (**
 IN PVOID Result OPTIONAL,
 IN ULONG ResultLength,
 IN NTSTATUS Status);
- **Used to resume execution in the kernel after a user-mode callback**
- **Copies the result of the callback back to the original kernel stack**
- **Restores original trap frame and kernel stack by using the information held in the KSTACK_AREA**
- **Deletes the kernel callback stack upon completion**

Applications of User-Mode Callbacks

- **User-mode callbacks allow win32k to perform a variety of tasks**
 - Invoke application-specific windows hooks
 - Provide event notification
 - Copy data to and from user-mode (e.g. for DDE)
- **Hooks allow users to execute code in response to certain actions performed by win32k**
 - Calling a window procedure
 - Creating or destroying a window
 - Processing keyboard or mouse input

CreateWindow CBT Hook Example



Kernel Attacks through User-Mode Callbacks

Vulnerabilities in Win32k

User Critical Section vs. Callbacks

- **Whenever a callback is executed, the kernel leaves the win32k user critical section**
 - Allows win32k to perform other tasks while user-mode code is being executed
- **Upon returning from a callback, win32k must ensure that referenced objects are still in the expected state**
 - E.g. a callback could call SetParent() to update the parent of a window
- **Insufficient checks may lead to vulnerabilities**

Function Name Decoration

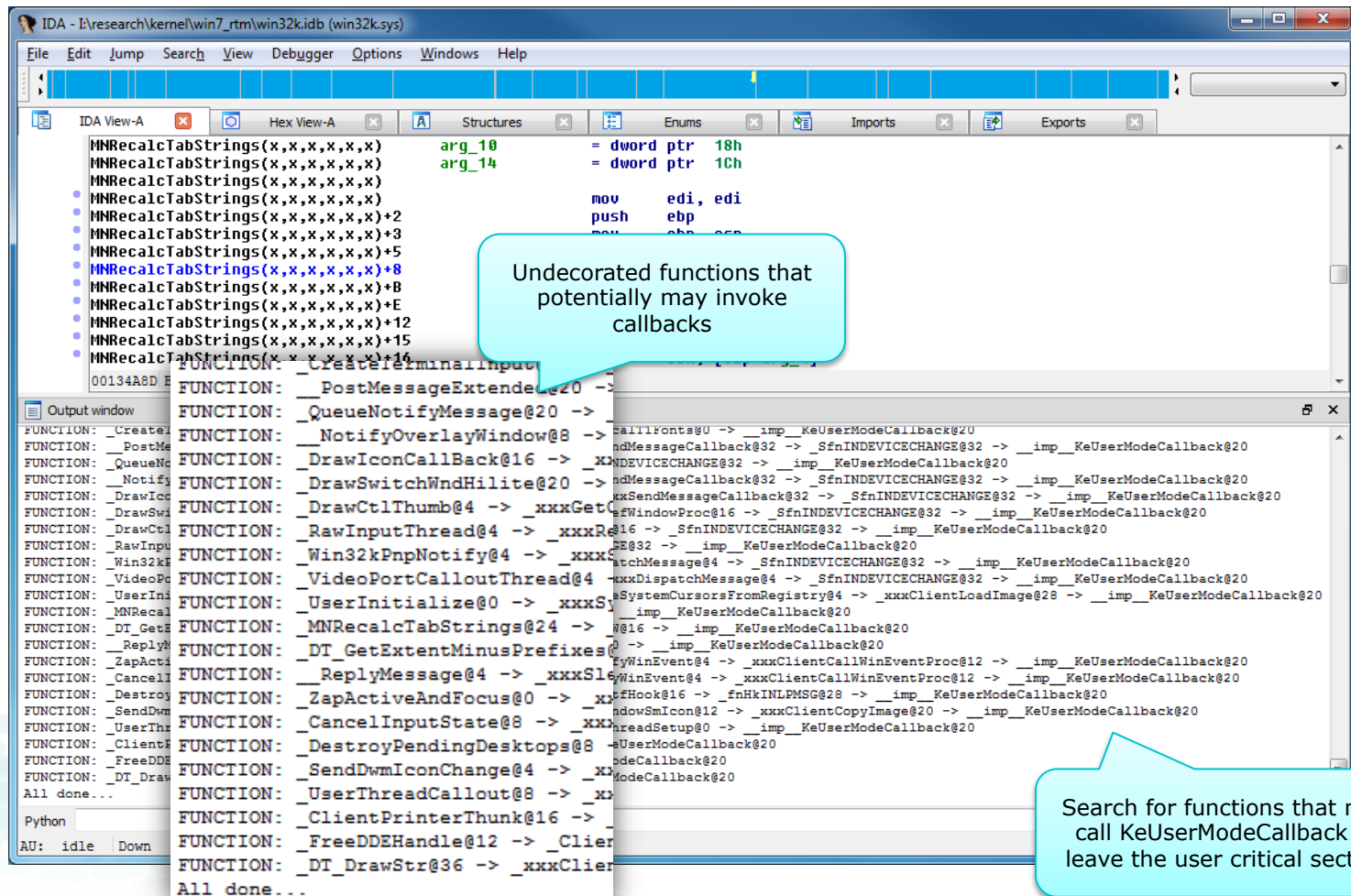
- **Win32k.sys** uses function name decoration to keep track of functions that leave the critical section
 - Prefixed “xxx” and “zzz”
- **Functions prefixed “xxx” may leave the critical section and invoke a user-mode callback**
 - May sometimes require a specific argument or set of arguments to trigger the actual callback
- **Functions prefixed “zzz” typically invoke a deferred event callback**
 - However, if win32k!gdwDeferWinEvent is null, an immediate callback is performed

Function Name Decoration Issues

- **Functions that leave the critical section and invoke user-mode callbacks are not always prefixed**
 - Could lead to invalid assumptions by the programmer
 - Easy to spot using IDAPython and cross referencing
- **Lack of consistency in behavior of “zzz” functions**
 - Some “zzz” functions seem to increment `gdwDeferWinEvent` while others do not

Windows 7 RTM	Windows 7 (MS11-034)
MNRecalcTabStrings	xxxMNRecalcTabStrings
FreeDDEHandle	xxxFreeDDEHandle
ClientFreeDDEHandle	xxxClientFreeDDEHandle

Locating Undecorated Functions



Object Locking

- Objects expected to be valid after the kernel leaves the user critical section must be *locked*
 - The *cLockObj* field of the user object header stores the object reference count
- **Two forms of locking**
 - Thread locking
 - Assignment locking

Thread Locking

- **Used to lock objects or buffers within the context of a thread**
 - ThreadLock* (inlined mostly) and ThreadUnlock*
- **Each thread locked entry is stored as a TL structure in a thread-specific thread lock list**
 - kd> dt win32k!_TL
 - +0x000 next : Ptr32 _TL
 - +0x004 pObj : Ptr32 Void
 - +0x008 pfnFree : Ptr32 Void
- **Upon thread termination, the thread lock list is processed to release any outstanding entries**
 - xxxDestroyThreadInfo -> DestroyThreadsObjects

Thread Locking By Example

```
NtUserDragDetect(x,x,x)
NtUserDragDetect(x,x,x)
NtUserDragDetect(x,x,x) ; Attributes: bp-based frame
NtUserDragDetect(x,x,x) ; _stdcall NtUserDragDetect(x, x, x)
NtUserDragDetect(x,x,x) _NtUserDragDetect@12 proc near
NtUserDragDetect(x,x,x)
NtUserDragDetect(x,x,x) t1= _TL ptr -0Ch
NtUserDragDetect(x,x,x) hwnd= dword ptr 8
NtUserDragDetect(x,x,x) arg_4= dword ptr 0Ch
NtUserDragDetect(x,x,x) arg_8= dword ptr 10h
NtUserDragDetect(x,x,x)
NtUserDragDetect(x,x,x) mov edi, edi
NtUserDragDetect(x,x,x)+2 push ebp
NtUserDragDetect(x,x,x)+3 mov ebn, esp
NtUserDragDetect(x,x,x)
NtUserDragDetect(x,x,x)+1E
NtUserDragDetect(x,x,x)+1E
NtUserDragDetect(x,x,x)+1E
NtUserDragDetect(x,x,x)+24
NtUserDragDetect(x,x,x)+2A
NtUserDragDetect(x,x,x)+2C
NtUserDragDetect(x,x,x)+2F
NtUserDragDetect(x,x,x)+32
NtUserDragDetect(x,x,x)+34
NtUserDragDetect(x,x,x)+3E
NtUserDragDetect(x,x,x)+40
NtUserDragDetect(x,x,x)+41
NtUserDragDetect(x,x,x)+46
NtUserDragDetect(x,x,x)+48
```

```
loc_BF95667F:
mov     ecx, _gptiCurrent
add     ecx, tagTHREADINFO.pt1
mov     edx, [ecx]
mov     [ebp+t1.next], edx
lea     edx, [ebp+t1]
mov     [ecx], edx
mov     [ebp+t1.pobj], eax
inc     [eax+tagWND.head.cLockObj]
push    [ebp+arg_8]
push    [ebp+arg_4]
push    eax
call    _xxxDragDetect@12 ; xxxD
mov     esi, eax
call    _ThreadUnlock1@0 ; ThreadUnlock1()
```

xxx function = possible callback

Thread lock entry added to TL list

Object lock count incremented

Thread lock released

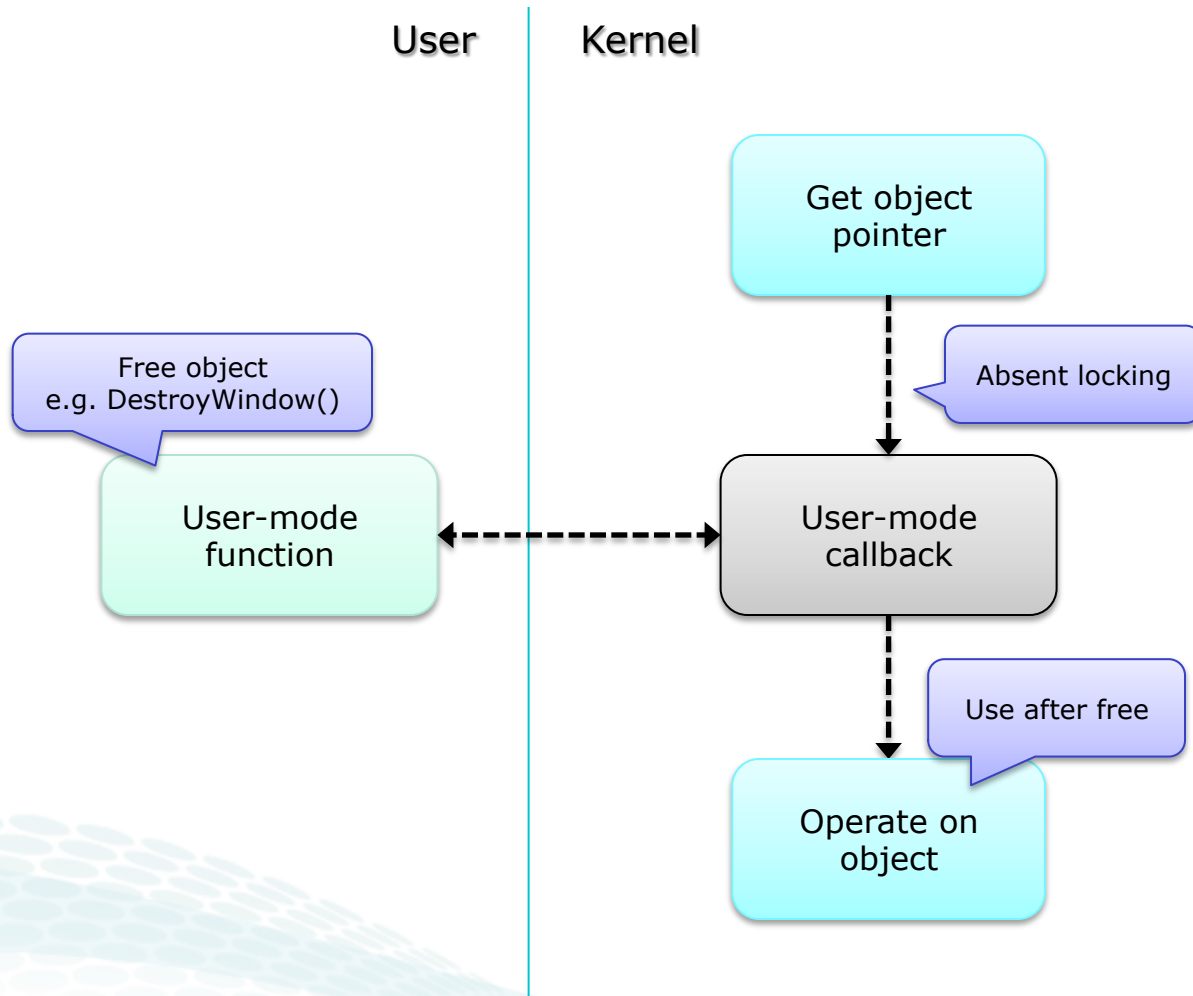
Assignment Locking

- **The handle manager provides functions for thread independent locking of objects**
 - `HMAssignmentLock(Address, Object)`
 - `HMAssignmentUnlock(Address)`
- **Assignment locking an object to an address with an initialized pointer, releases the existing reference**
- **Does not provide the safety net thread locking does**
 - E.g. if a thread termination occurs in a callback, the thread cleanup code must release these references

Object Locking Vulnerabilities

- Any object expected to be valid after a user-mode callback should be locked
- Similarly, any object that no longer is used by a particular component should be released
- Mismanagement in the locking and release of objects could result in the following
 - No retention: An object could be freed too early
 - No release: An object could never be freed, or the reference count (e.g. 32-bit on x86) could wrap

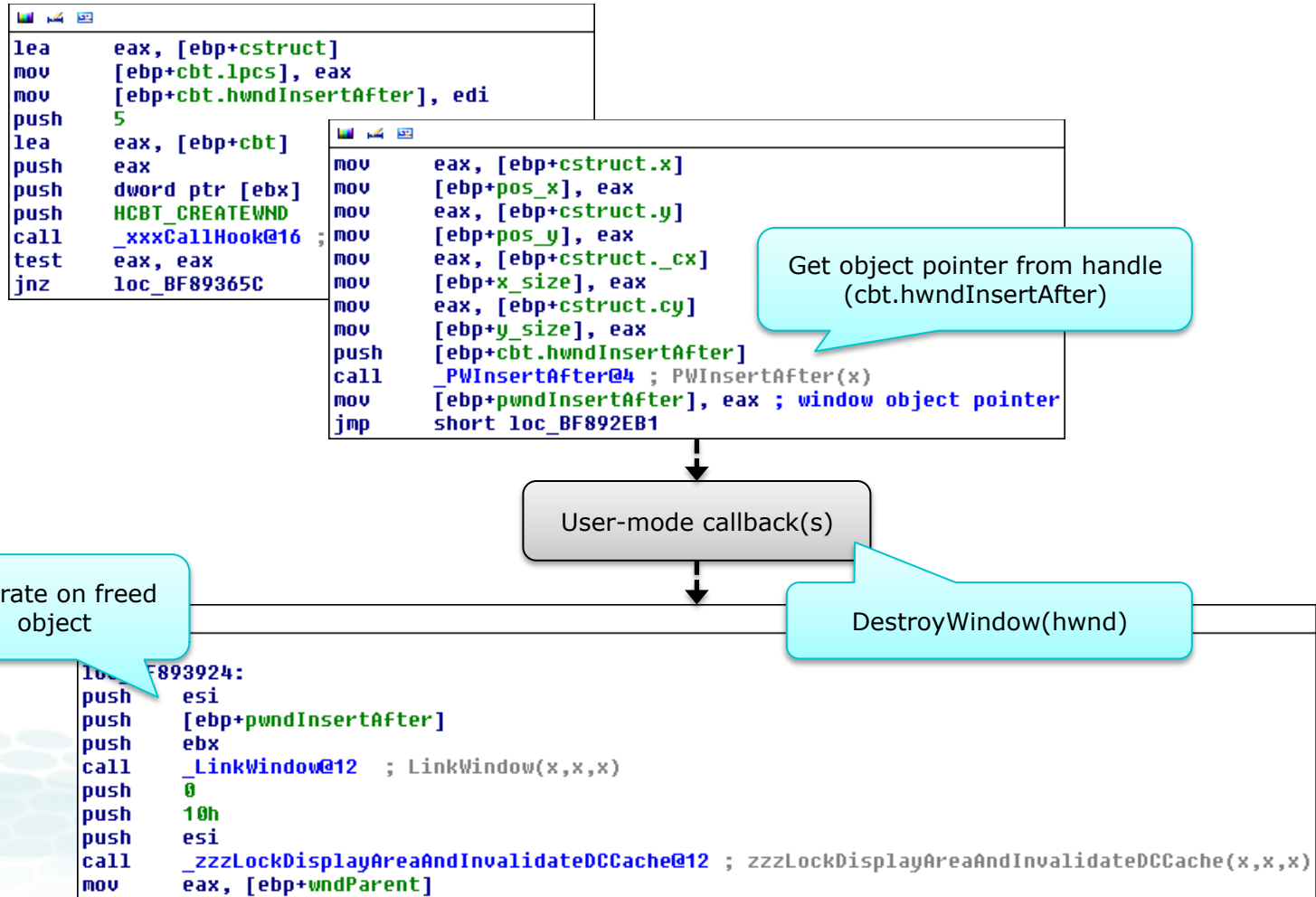
Object Use-After-Free



Window Object Use-After-Free

- In creating a window, an application can adjust its orientation and z-order using a CBT hook
 - Z-order is defined by providing the handle to the window after which the new window is inserted
- **win32k!xxxCreateWindowEx failed to properly lock the provided z-order window**
 - Only stored a pointer to the object in a local variable
- **An attacker could destroy the window in a subsequent user-mode callback and trigger a use-after-free**

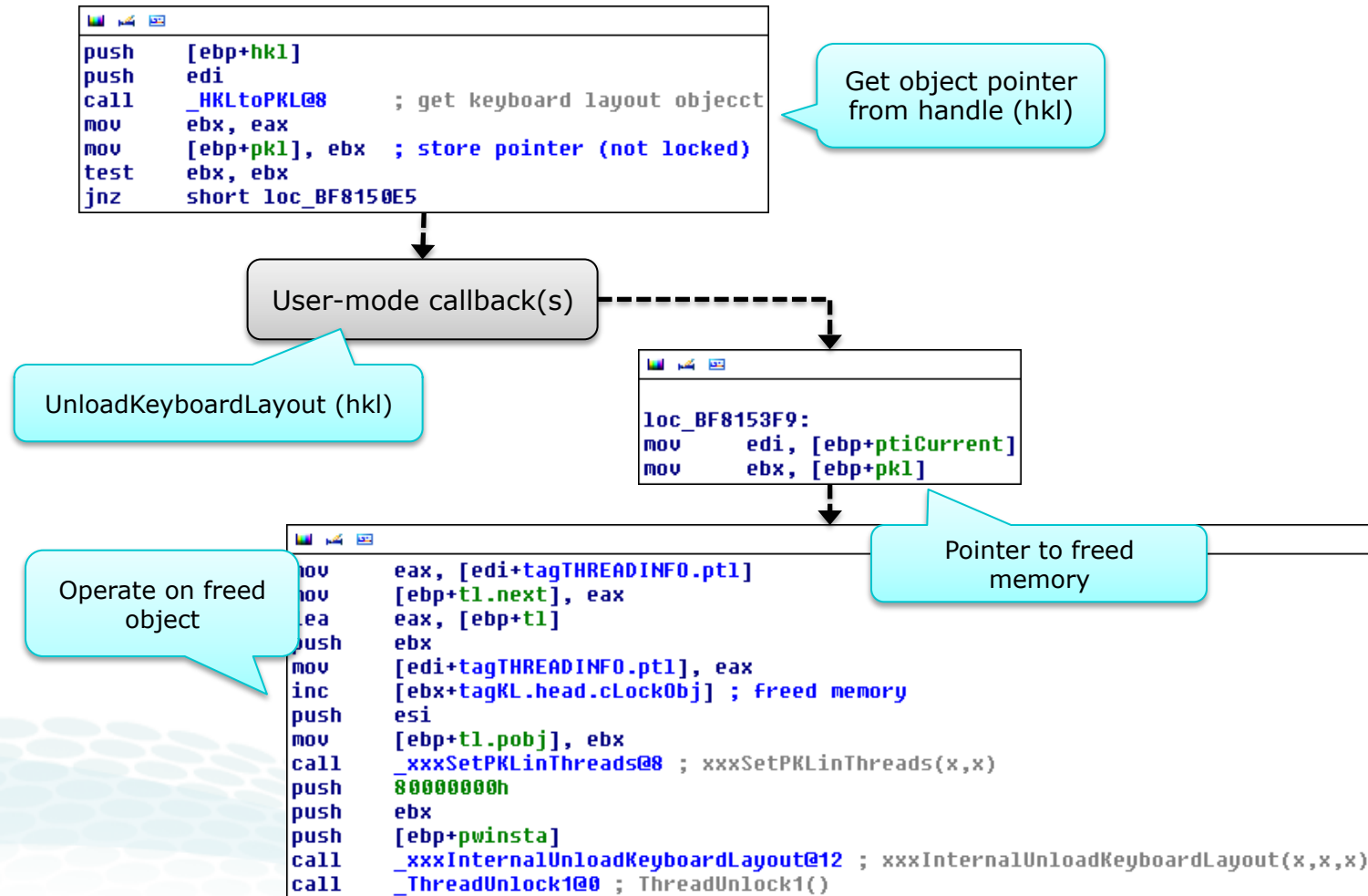
Window Object Use-After-Free



Keyboard Layout Object Use-After-Free

- In loading a keyboard layout, win32k! `xxxLoadKeyboardLayoutEx` did not lock the keyboard layout object
 - Pointer stored in local variable
- An attacker could unload the keyboard layout in a user-mode callback and thus free the object
- Subsequently, upon using the object pointer the kernel would operate on freed memory

Keyboard Layout Object Use-After-Free



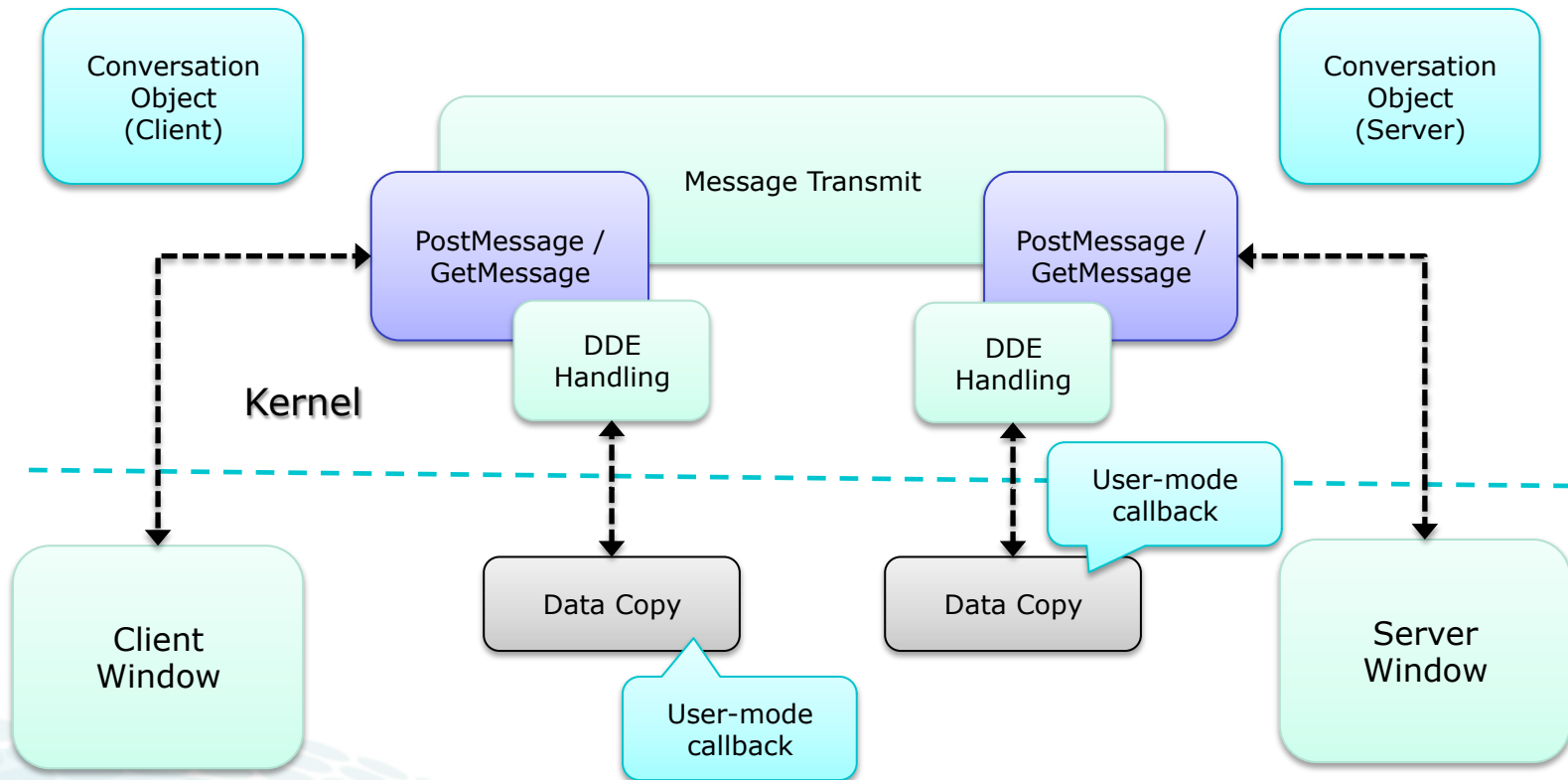
Object State Validation

- **Objects assumed to be in a certain state should always have their state validated**
 - Usually involves checking for initialized pointers or flags
- **User-mode callbacks could alter the state and update properties of objects**
 - A drop down menu is no longer active
 - The parent of a window has changed
 - The partner in a DDE conversation terminated

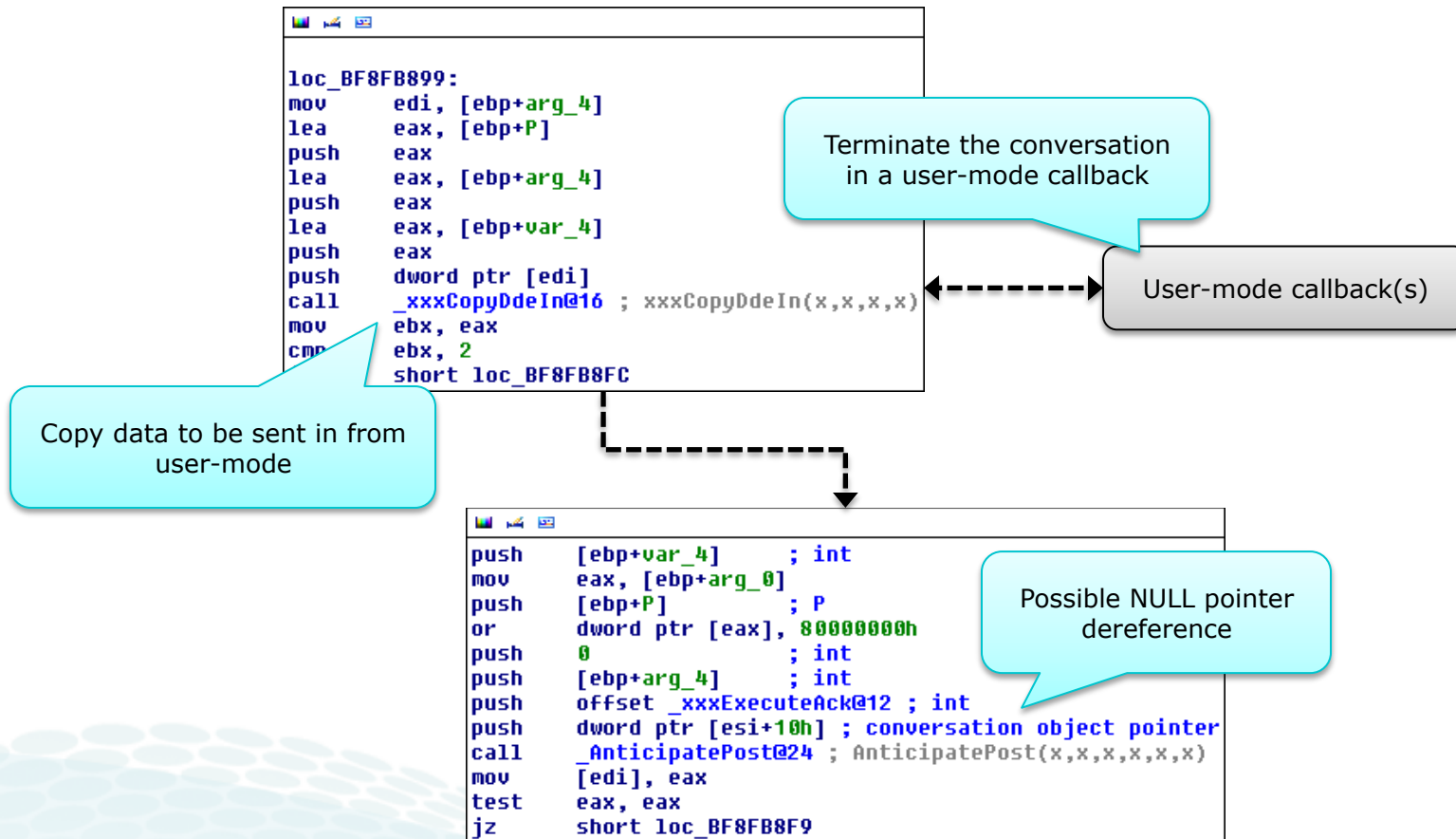
DDE Conversation State Vulnerabilities

- **Dynamic Data Exchange (DDE)**
 - Legacy protocol using messages and shared memory to exchange data between applications
- **Several functions did not sufficiently validate DDE conversation objects after user-mode callbacks**
 - Used to copy data in and out from user-mode
- **An attacker could terminate a conversation in a user-mode callback and thus unlock the partner conversation object**
 - Could result in a NULL pointer dereference as the function did not revalidate the conversation object pointer

DDE Conversation Message Handling



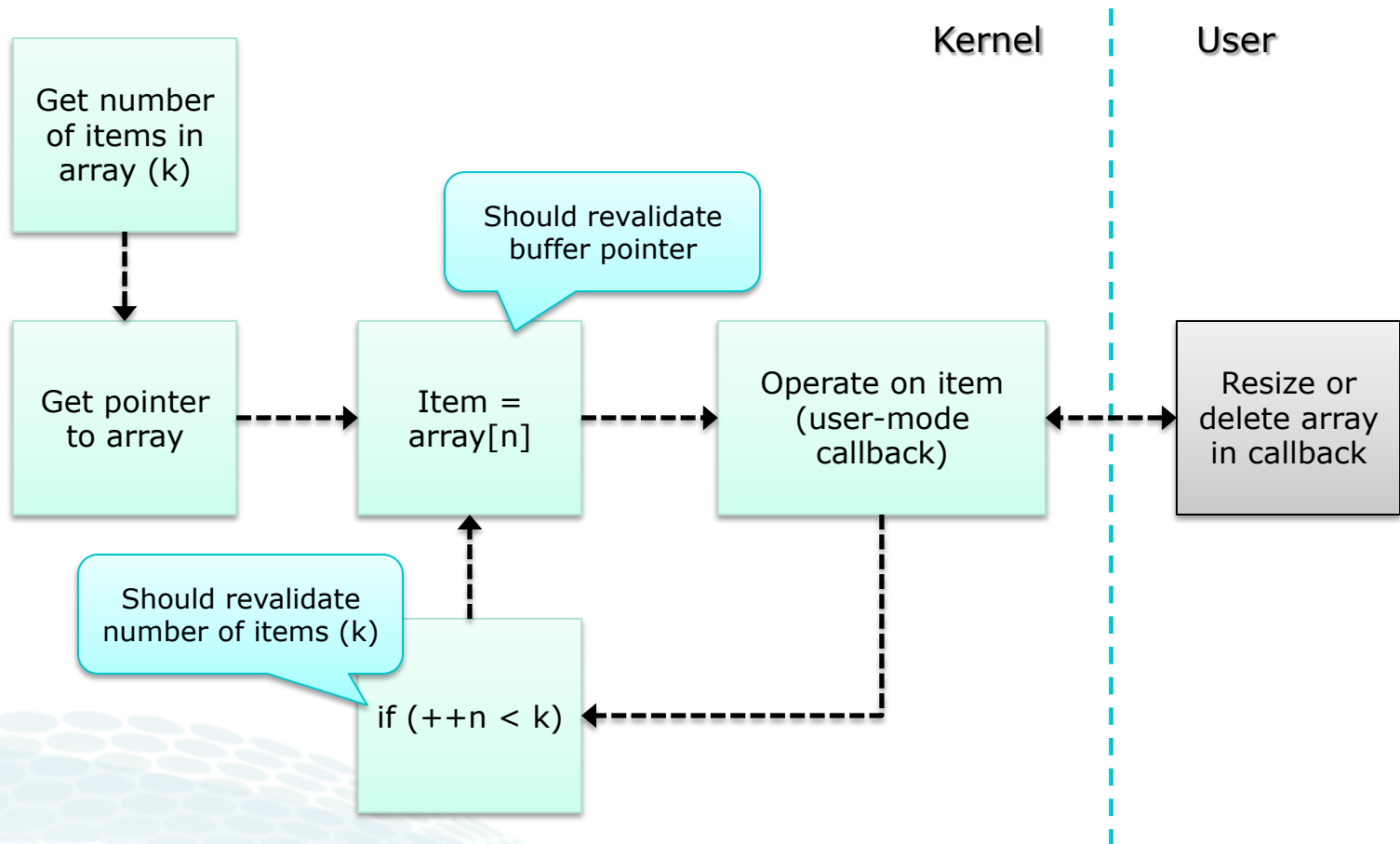
DDE Conversation Object NULL Dereference



Buffer Reallocation

- **Many user objects have item arrays or other forms of buffers associated with them**
 - E.g. menu items array
- **Item arrays where elements are added or removed are often resized to conserve memory**
 - Buffer freed if the array is empty
 - Buffer reallocated if elements is above or below a certain threshold
- **Any buffer that can be reallocated or freed during a callback must be checked upon return**
 - Failure to do so could result in use-after-free

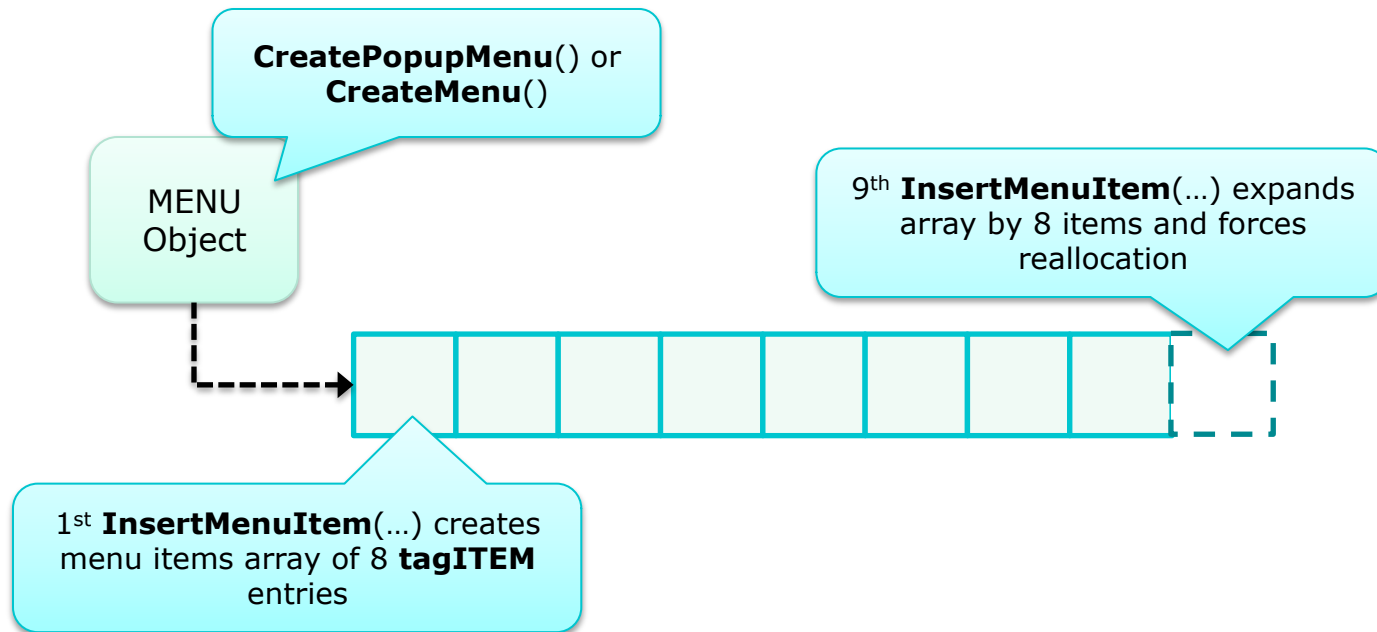
Buffer Reallocation



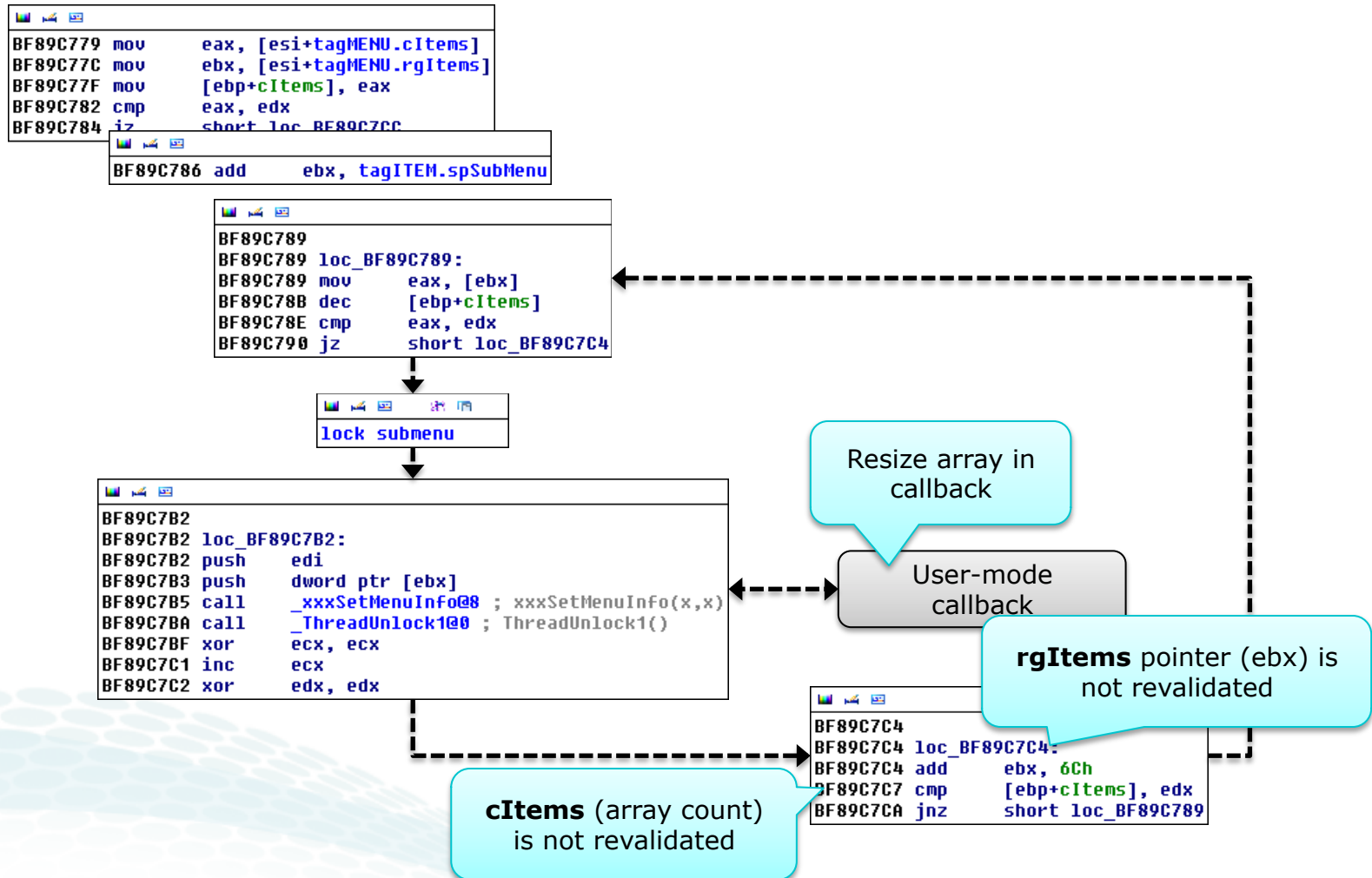
Menu Item Array Use-After-Frees

- **Menus may hold an arbitrary number of menu items**
 - Stored in a dynamically sized array pointed to by the menu object structure (win32k!tagMENU)
- **Win32k did not revalidate the menu items array pointer after user-mode callbacks**
 - No way to “lock” a menu item
 - Any ‘xxx’ function operating on menu items was potentially vulnerable
- **An attacker could cause the buffer to be reallocated in a callback and trigger a use-after-free**

Menu Item Array Reallocation



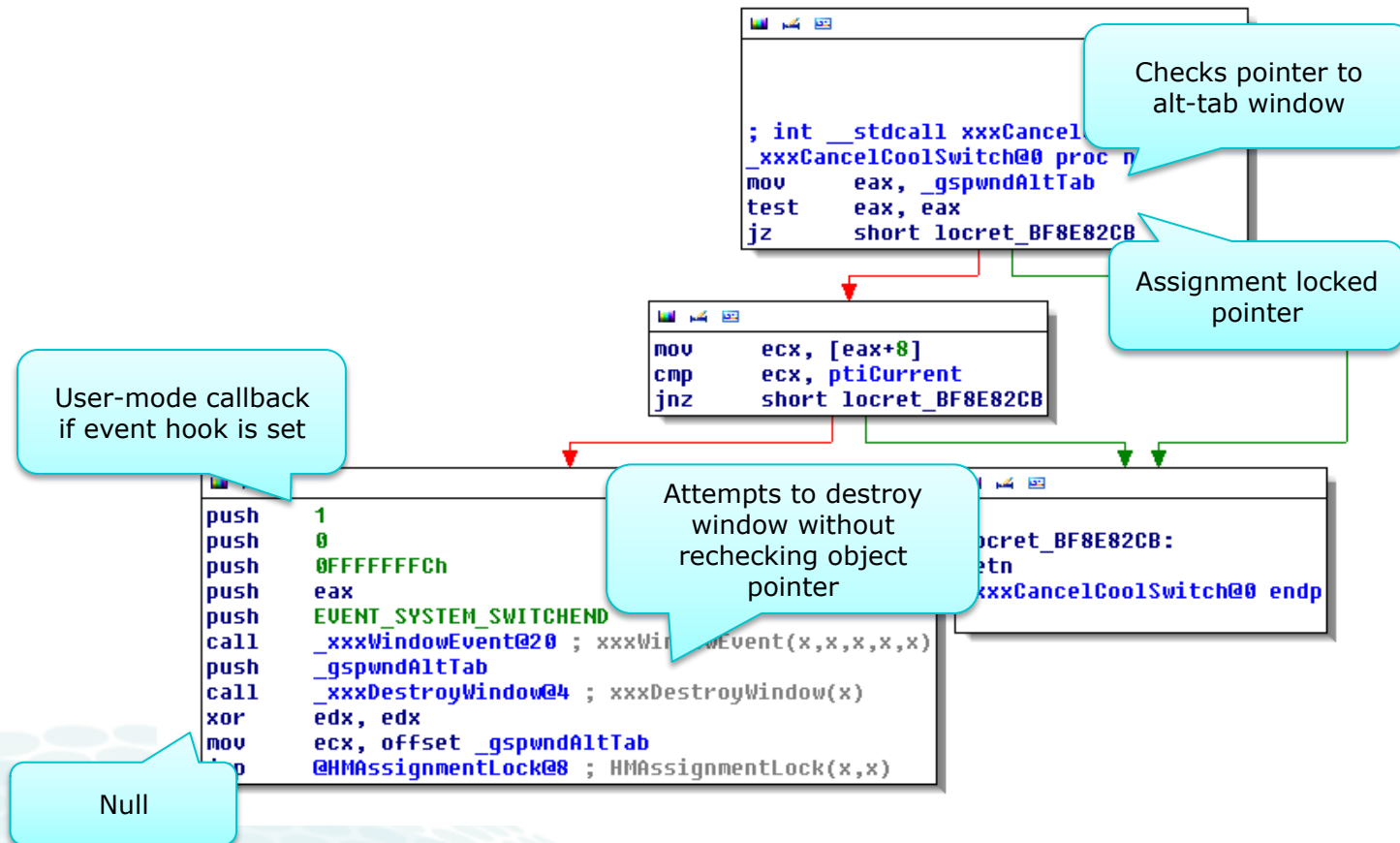
Menu Item Processing Use-After-Free



Time-of-Check-to-Time-of-Use

- **The user critical section is generally used to prevent TOCTTOU issues in user object handling**
 - User-mode callbacks may allow an attacker to manipulate an object or global value before it is used
- **Can be particularly dangerous in clean up routines**
 - May invoke callbacks after checks have been made
 - Could result in stale references to objects or buffers
- **Values that may have changed must always be (re)checked after a callback has taken place**

Time-of-Check-to-Time-of-Use



Handle Validation

- **Required to validate handles, their type, and retrieve the corresponding object pointers**
 - HMValidateHandle() and friends
- **Generic handle validation should be avoided unless the structure of the object is irrelevant**
 - Only checks handle table entry and ignores type
- **Functions that revalidate handles after callbacks, may no longer be operating on the same object**
 - The uniqueness counter designed to provide handle entropy is only 16-bit

Insufficient Handle Validation

```
xxxGetMenuBarInfo(x,x,x,x)+297 mov     edi, [ebp+pwnd]
xxxGetMenuBarInfo(x,x,x,x)+29A push    ecx
xxxGetMenuBarInfo(x,x,x,x)+29B push    ecx
xxxGetMenuBarInfo(x,x,x,x)+29C push    1E1h
xxxGetMenuBarInfo(x,x,x,x)+2A1 push    edi
xxxGetMenuBarInfo(x,x,x,x)+2A2 call     _xxxSendMessage@16 ; xxxSendMessage(x,x,x,x)
xxxGetMenuBarInfo(x,x,x,x)+2A7 mov     edx, _ahelist ; handle table pointer
xxxGetMenuBarInfo(x,x,x,x)+2AD mov     ecx, eax ; eax: user handle
xxxGetMenuBarInfo(x,x,x,x)+2AF and     ecx, 0FFFFh
xxxGetMenuBarInfo(x,x,x,x)+2B5 lea     ecx, [ecx+ecx*2]
xxxGetMenuBarInfo(x,x,x,x)+2B8 mov     ecx, [edx+ecx*4]
xxxGetMenuBarInfo(x,x,x,x)+2BB test    ecx, ecx ; ecx: object pointer
xxxGetMenuBarInfo(x,x,x,x)+2BD jz      loc_BF91E14B
```

Function did not check
handle type nor validate
index in handle table

Function did not check that
object was an image (icon/
cursor)

```
xxxClientLoadImage(x,x,x,x,x,x,x)+16D or      dl, 0FFh ; TYPE_GENERIC
xxxClientLoadImage(x,x,x,x,x,x,x)+170 mov     ecx, edi ; handle from user-mode callback
xxxClientLoadImage(x,x,x,x,x,x,x)+172 call     @HMValidateHandleNoRip@8 ; HMValidateHandleNoRip(x,x)
xxxClientLoadImage(x,x,x,x,x,x,x)+177 mov     edi, eax
```

Exploitability

Use-After-Frees and NULL Pointer
Dereferences

Vulnerability Primitives

- **Mainly dealing with two vulnerability primitives**
 - Use-After-Frees
 - Null-Pointer Dereferences
- **Exploitability may depend on the attacker's ability to manipulate heap and pool memory**
 - Kernel Pool Exploitation on Windows 7 (BH DC '11)
 - Not much public information on the kernel heap
- **Hooking user-mode callbacks is easy**
 - `NtCurrentPeb()->KernelCallbackTable`

Kernel Heap

- **The kernel has a stripped down version of the user-mode heap allocator**
 - `nt!RtlAllocateHeap`, `nt!RtlFreeHeap`, etc.
 - Used by the shared and desktop heaps
- **Neither heaps employ any front end allocators**
 - `ExtendedLookup == NULL`
 - No low fragmentation heap or lookaside lists
- **Neither heaps encode or obfuscate heap management structures**
 - `HEAP.EncodeFlagMask == 0`

Desktop Heap Base

The screenshot shows a WinDbg kernel memory dump of the Desktop Heap Base structure. The structure is located at address 0x00000000. The dump shows various fields, including CompatibilityFlags, EncodeFlagMask, Encoding, PointerKey, and others. Annotations highlight specific fields and their values:

- EncodingFlagMask and PointerKey:** A callout points to the `EncodeFlagMask` (0x00000000) and `PointerKey` (0x00000000) fields.
- No front end allocators:** A callout points to the `FrontEndHeap` field, which is set to 0.
- Free list:** A callout points to the `FreeLists` field, which is a `_LIST_ENTRY` pointing to 0x00000000.
- Commit routine to extend the heap:** A callout points to the `CommitRoutine` field, which is a pointer to `win32k!UserCommitDesktopMemory+0`.

```
kd> dt nt!_HEAP_LIST_LOOKUP fea00138
+0x000 ExtendedLookup : (null)
+0x004 ArraySize : 0x80
+0x008 ExtraItem : 1
+0x00c ItemCount : 0x1f
+0x010 OutOfRangeItems : 2
+0x014 BaseIndex : 0
+0x018 ListHead : 0xfea000c4 _LIST_ENTRY [ 0xfea14008 - 0xfea1d980 ]
+0x01c ListsInUseUlong : 0xfea0015c -> 0x2010338
+0x020 ListHints : 0xfea0016c -> (null)
kd> dt nt!_HEAP 5b0000
+0x048 CompatibilityFlags : 0
+0x04c EncodeFlagMask : 0
+0x050 Encoding : _HEAP_ENTRY
+0x058 PointerKey : 0
+0x05c Interceptor : 0
+0x060 VirtualMemoryThreshold : 0xfe00
+0x064 Signature : 0xeeffefff
+0x068 SegmentReserve : 0x100000
+0x06c SegmentCommit : 0x2000
+0x070 DeCommitFreeBlockThreshold : 0x200
+0x074 DeCommitTotalFreeThreshold : 0x2000
+0x078 TotalFreeSize : 0x5a9
+0x07c MaximumAllocationSize : 0x7fff
+0x080 ProcessHeapsListIndex : 0
+0x082 HeaderValidateLength : 0x138
+0x084 HeaderValidateCopy : (null)
+0x088 NextAvailableTagIndex : 0
+0x08a MaximumTagIndex : 0
+0x08c TagEntries : (null)
+0x090 UCRLList : _LIST_ENTRY [ 0xfea00010 - 0xfea00010 ]
+0x098 AlignRound : 0xf
+0x09c AlignMask : 0xffffffff
+0x0a0 VirtualAllocdBlocks : _LIST_ENTRY [ 0xfea00000 - 0xfea00000 ]
+0x0a8 SegmentList : _LIST_ENTRY [ 0xfea00010 - 0xfea00010 ]
+0x0b0 AllocatorBackTraceIndex : 0
+0x0b4 NonDedicatedListLength : 0
+0x0b8 BlocksIndex : 0xfea00138 Void
+0x0bc UCRIndex : (null)
+0x0c0 PseudoTagEntries : (null)
+0x0c4 FreeLists : _LIST_ENTRY [ 0xfea14008 - 0xfea1d980 ]
+0x0cc LockVariable : (null)
+0x0d0 CommitRoutine : 0x93bb69e9 long win32k!UserCommitDesktopMemory+0
+0x0d4 FrontEndHeap : (null)
+0x0d8 FrontHeapLockCount : 0
+0x0da FrontEndHeapType : 0
+0x0dc Counters : _HEAP_COUNTERS
```

Kernel Heap Management

- **Freed memory is indexed into a single free list**
 - Ordered by block size
 - *ListHints* used to optimize list lookup
- **Requested memory is always pulled from the front of an oversized heap chunk**
 - Remaining fragment is put back into the free list
- **If the heap runs out of committed memory, win32k calls the *CommitRoutine* to extend the heap**
 - Attempts to commit memory from the reserved range
 - E.g. win32k reserves 0xC00000 bytes by default (adjustable by user) for desktop heaps

Use-After-Free Exploitation

- **Unicode strings can be used to reallocate freed memory from within user-mode callbacks**
 - Allows control of the contents and size of the heap block
 - Caveat: Cannot use WORD NULLs and last two bytes must be NULL to terminate the string
- **Desktop heap**
 - `SetWindowTextW(hWnd, String);`
- **Session pool**
 - `SetClassLongPtr(hWnd, GCLP_MENUNAME, (LONG)String);`

Strings As User Objects

Kernel 'com:pipe,reset=0,reconnect,port=\\.\pipe\kd_Windows_7' - WinDbg:6.12.0002.633 AMD64

File Edit View Debug Window Help

Disassembly

Offset: @\$scopeip

```
92da5f3b 894808 mov     dword ptr [eax+8],ecx
92da5f3e 8b4608 mov     eax,dword ptr [esi+8]
92da5f41 8b4e0c mov     ecx,dword ptr [esi+0Ch]
92da5f44 89480c mov     dword ptr [eax+0Ch],ecx
92da5f47 8b4708 mov     eax,dword ptr [edi+8]
92da5f4a 894608 mov     dword ptr [esi+8],eax
92da5f4d 897e0c mov     dword ptr [esi+0Ch],edi
92da5f50 8b4708 mov     eax,dword ptr [edi+8]
92da5f53 89700c mov     dword ptr [eax+0Ch],esi ds:0023:4141414d=???????
92da5f56 897708 mov     dword ptr [edi+8],esi
92da5f59 5f      pop     edi
92da5f5a 5e      pop     esi
92da5f5b 5b      pop     ebx
92da5f5c c9      leave
92da5f5d c20800 ret     8
92da5f60 90      nop
92da5f61 90      nop
```

Command - Kernel 'com:pipe,reset=0,reconnect,port=\\.\pipe\kd_Windows_7' - WinDbg:6.12.0002.633 AMD64

```
kd> g
Access violation - code c0000005 (!!! second chance !!!)
win32k!xxxSetPKLinThreads+0xa9:
92da5f53 89700c mov     dword ptr [eax+0Ch],esi
kd> r
eax=41414141 ebx=00000000 ecx=ffb222c8 edx=8c436f00 esi=ffb11df0 edi=ffa410c8
eip=92da5f53 esp=968408d4 ebp=968408f0 iopl=0         nv up ei pl nz na po cy
cs=0008  ss=0010  ds=0023  fs=0030  gs=0000             efl=00010203
win32k!xxxSetPKLinThreads+0xa9:
92da5f53 89700c mov     dword ptr [eax+0Ch],esi ds:0023:4141414d=???????
kd> dd edi
ffa410c8 41414141 41414142 41414141 41414141
ffa410d8 41414141 41414141 41414141 41414141
ffa410e8 41414141 41414141 41414141 41414141
ffa410f8 41414141 41414141 41414141 41414141
ffa41108 00004141 88853c40 4609000a 6c6d7355
ffa41118 00000000 00000000 00000000 00000000
ffa41128 00000000 00000000 00000000 00000000
ffa41138 00000000 00000000 00000000 00000000
```

Registers

Customize...

Reg	Value
edi	ffa410c8
esi	ffb11df0
ebx	0
edx	8c436f00
ecx	ffb222c8
eax	41414141
ebp	968408f0
eip	92da5f53
cs	8
efl	10203
esp	968408d4
ss	10
eax	0

Arbitrary memory corruption

Unicode string allocated in place of freed object

Ln 0, Col 0 Sys 0:KdSrv:S Proc 000:0 Thrd 000:0 ASM OVR CAPS NUM

Exploiting Object Locking Behavior

- **Embedded object pointers in the freed object may allow an attacker to increment (lock) or decrement (unlock) an arbitrary address**
 - Common behavior of locking routines
- **Some targets**
 - **HANDLEENTRY.bType**
 - Decrement the type of a window handle table entry (1)
 - Destroy routine for free type (0) is null (mappable by user)
 - **KAPC.ApcMode**
 - Execute code with kernel-mode privileges by decrementing UserMode (1) to KernelMode (0)

Exploiting Object Locking Behavior

Kernel 'com:pipe,reset=0,reconnect,port=\\.\pipe\kd_Windows_7' - WinDbg:6.12.0002.633 AMD64

File Edit View Debug Window Help

Disassembly

Offset: @\$scopeip

```
8216c555 90      nop
win32k!HMutexUnlockObject:
8216c556 8bff    mov     edi,edi
8216c558 55      push   ebp
8216c559 8bec    mov     ebp,esp
8216c55b 8b4508  mov     eax,dword ptr [ebp+8]
8216c55e ff4804  dec     dword ptr [eax+4]  ds:0023:deadbeef=????????
8216c561 7506    jne     win32k!HMutexUnlockObject+0x13 (8216c569)
8216c563 50      push   eax
8216c564 e8cf3a0000 call    win32k!HMutexUnlockObjectInternal (82170038)
8216c569 5d      pop     ebp
8216c56a c20400  ret     4
8216c56d 90      nop
```

Unlocking user-controlled pointer (0xdeadbeef)

Command - Kernel 'com:pipe,reset=0,reconnect,port=\\.\pipe\kd_Windows_7' - WinDbg:6.12.0002.633 AMD64

```
kd> r
eax=deadbeef ebx=fe95a990 ecx=ff910000 edx=fea11480 esi=fea11480 edi=deadbeef
eip=8216c55e esp=9431dca0 ebp=9431dca0 iopl=0         nv up ei ng nz na pe nc
cs=0008  ss=0010  ds=0023  es=0023  fs=0030  gs=0000             efl=00000286
win32k!HMutexUnlockObject+0x8:
8216c55e ff4804  dec     dword ptr [eax+4]  ds:0023:deadbeef=????????
kd> kb
ChildEBP RetAddr  Args to Child
9431dca0 8216c9e0  deadbeef  00000000  fe95a978  win32k!HMutexUnlockObject+0x8
9431dcb0 820d0cb1  820d0b8b  0048fa0c  002af85c  win32k!HMAssignmentLock+0x45
9431dcc8 820d0bb3  9431dcfc  9431dcf4  9431dcf4  win32k!xxxCsDdeInitialize+0x67
9431dd18 8285542a  0048fa0c  0048fa1c  0048fa14  win32k!NtUserDdeInitialize+0x28
9431dd18 779464f4  0048fa0c  0048fa1c  0048fa14  nt!KiFastCallEntry+0x12a
002af91c 7795b3f5  7ffdf000  77a4624b  00000000  ntdll!KiFastSystemCallRet
002af95c 7795b3c8  00fe16e2  7ffdf000  00000000  ntdll!_RtlUserThreadStart+0x70
002af974 00000000  00fe16e2  7ffdf000  00000000  ntdll!_RtlUserThreadStart+0x1b
```

HMAssignmentLock unlocks the existing user-controlled pointer

Ln 0, Col 0 Sys 0:KdSrv:S Proc 000:0 Thrd 000:0 ASM OVR CAPS NUM

NULL Pointer Vulnerabilities

- **Potentially exploitable on the Windows platform**
 - Non-privileged users can map the null page, e.g. via `NtAllocateVirtualMemory` or `NtMapViewOfFile`
- **Many NULL pointer vulnerabilities are concerned with window object pointers**
- **An attacker could map the null page and set up a fake window object**
 - E.g. define a server-side window procedure and handle messages with kernel level privileges

NULL Pointer Object Exploitation

Kernel 'com:pipe,reset=0,reconnect,port=\\.\pipe\kd_WinXP_SP3_dev' - WinDbg:6.12.0002.633 AMD64

File Edit View Debug Window Help

Disassembly

Offset: @\$scopeip

No prior disassembly possible

41414141 ?? ???
41414142 ?? ???
41414143 ?? ???
41414144 ?? ???
41414145 ?? ???

Command - Kernel 'com:pipe,reset=0,reconnect,port=\\.\pipe\kd_WinXP_SP3_dev' - WinDbg:6.12.0002.633 AMD64

kd> r
eax=00004688 ebx=00000002 ecx=f06e0688 edx=00000000 esi=00000000 edi=e105d830
eip=41414141 esp=f06e0634 ebp=f06e0670 iopl=0 nv up e
cs=0008 ss=0010 ds=0023 es=0023 fs=0030 gs=0000
41414141 ?? ???
kd> kb 6
ChildEBP RetAddr Args to Child
WARNING: Frame IP not in any known module. Following frames:
f06e0630 bf814099 00000000 00000002 00000000 0x41414141
f06e0670 bf80ecc6 00000000 00000002 00000000 win32k!xxxSendMessageTimeout+0x18a
f06e0694 bf8457c1 00000000 00000002 00000000 win32k!xxxSendMessage+0x1b
f06e06d0 bf845ef6 00000000 00000000 e105d830 win32k!xxxDW_SendDestroyMessages+0x35
f06e071c bf8e82bf 00000000 bf91e8fa bc69eee0 win32k!xxxDestroyWindow+0x381
f06e0724 bf91e8fa bc69eee0 00000000 0000f040 win32k!xxxCancelCoolSwitch+0x2d
kd> dd 0
00000000 000200ac 00000000 e105d830 00000000
00000010 00000000 00040000 00000000 00000000
00000020 00000000 00000000 00000000 00000000
00000030 00000000 00000000 00000000 00000000
00000040 00000000 00000000 00000000 00000000
00000050 00000000 00000000 00000000 00000000
00000060 41414141 00000000 00000000 00000000
00000070 00000000 00000000 00000000 00000000

Message sent to null pointer object

Fake null page window object

Server-side window procedure pointer

Ln 0, Col 0 Sys 0:KdSrv:S Proc 000:0 Thrd 000:0 ASM OVR CAPS NUM

Demo

- **Window Object Use-After-Free (CVE-2011-1237)**
 - Arbitrary kernel code execution via HANDLEENTRY corruption

Mitigations

Protecting Against Privilege Escalation
Vulnerabilities

Mitigating Use-After-Free Exploitation

- **Need to address an attacker's ability to reallocate the freed memory before use**
- **Some approaches**
 - Delayed frees while processing a callback
 - Dedicated free lists for user objects
 - Isolate strings used in reallocating memory
 - Track allocations between ring transitions, e.g. pointers on the stack before a callback
- **Generally hard to mitigate without significantly impacting performance**

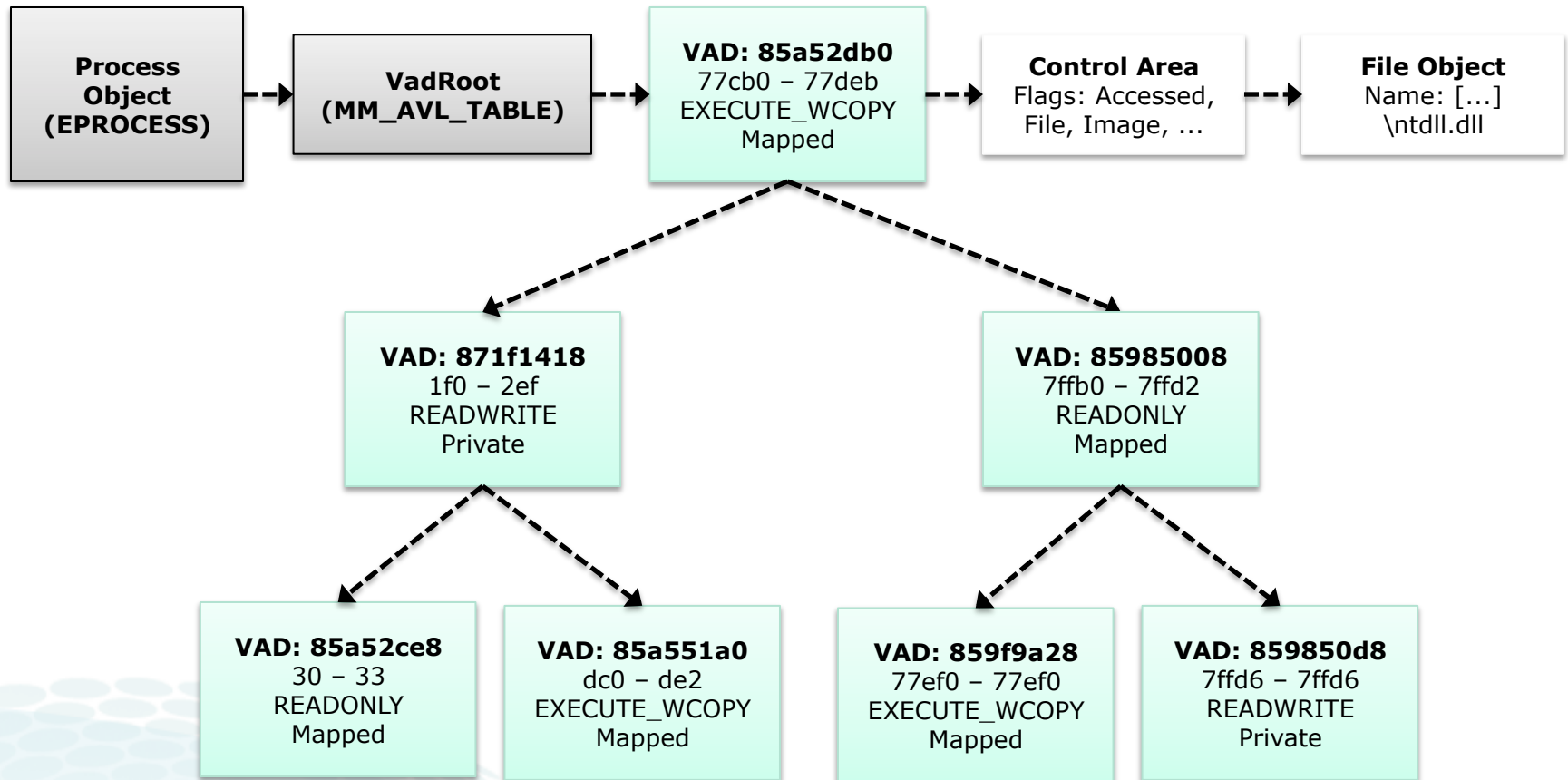
Mitigating NULL Pointer Exploitation

- We can address null pointer exploitation by denying users the ability to map the null page
- Some potential ways of addressing null page mappings
 - System call hooking
 - Page Table Entry (PTE) modification
 - VAD manipulation
- System call hooking not supported on x64
- PTE modification requires page to be mapped

VAD Manipulation

- **User mode process space is described using Virtual Address Descriptors (VADs)**
 - Structured in self-balanced AVL trees
- **VADs are always checked before PTEs are created**
 - E.g. used to implement the NO_ACCESS protection
- **VADs are used to secure memory, e.g. can be made non-deletable**
 - PEBs and TEBs
 - KUSER_SHARED_DATA section

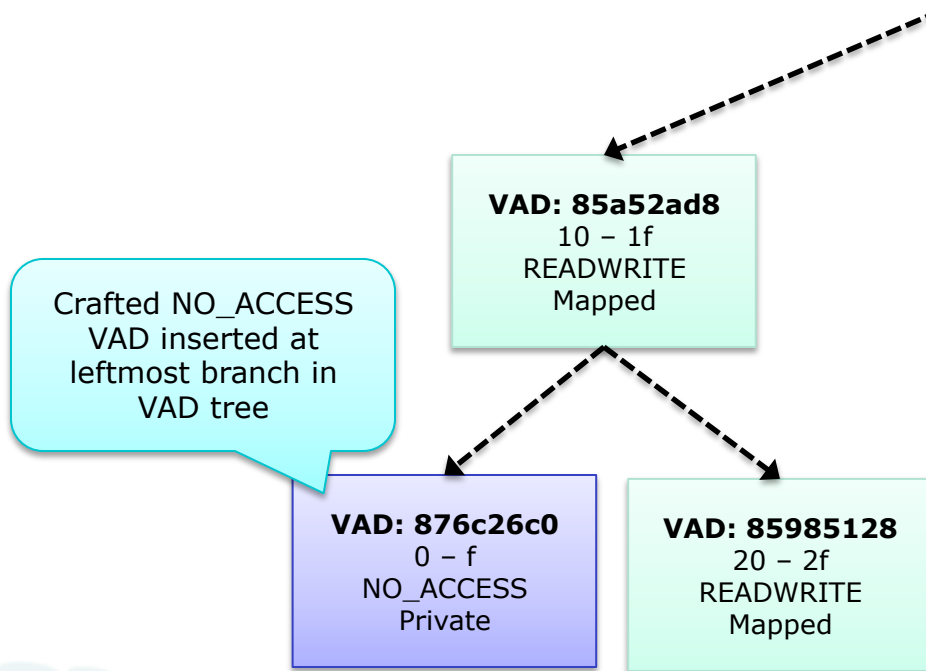
VAD Tree



Restricting Null Page Access

- **We insert a crafted VAD entry to restrict null page access**
 - Ring3 code cannot modify the VAD entry
- **Avoid deletion using the same method employed by PEBs and TEBs**
 - Secure address range from 0 up to 0xFFFF
 - Set protection to NO_ACCESS
- **Use a special VAD flag to prevent memory commits**
 - Protection cannot be changed on uncommitted memory!

VAD Tree /w Crafted Entry



Manipulated Process VAD Tree

Kernel 'com:pipe, resets=0, reconnect, port=\\.\pipe\kd_Windows_7' - WinDbg:6.12.0002.633 AMD64

File Edit View Debug Window Help

Command - Kernel 'com:pipe, resets=0, reconnect, port=\\.\pipe\kd_Windows_7' - WinDbg:6.12.0002.633 AMD64

```
kd> !process @$proc 0
PROCESS 85a61ab8 SessionId: 1 Cid: 0eec Peb: 7ffd9000 Pa
DirBase: 1f05b3e0 ObjectTable: 962db880 HandleCount: 6
Image: ktest.exe
```

kd> r? \$t0 = &((nt!_EPROCESS *)0)->VadRoot; !vad poi(@\$proc+\$t0+8);

VAD	level	start	end	commit			
859ded48	(4)	0	f	524287	Private	NO_ACCESS	
85a7f0d8	(3)	10	1f	0	Mapped	READWRITE	Pagefile-backed section
85aee360	(4)	20	2f	0	Mapped	READWRITE	Pagefile-backed section
866007f8	(2)	30	33	0	Mapped	READONLY	Pagefile-backed section
877f5e30	(3)	40	40	1	Private	READWRITE	
859aa0b8	(4)	50	b6	0	Mapped	READONLY	\Windows\System32\locale.nls
875c0390	(1)	1b0	2af	3	Private	READWRITE	
8778c140	(4)	400	40f	3	Private	READWRITE	
8719c0b0	(3)	430	52f	15	Private	READWRITE	
85a52eb8	(2)	1020	1042	6	Mapped Exe	EXECUTE_WRITECOPY	\Users\vmware\Desktop\ktest.exe\VMwareD
859f92f0	(4)	75f60	75fa9	3	Mapped Exe	EXECUTE_WRITECOPY	\Windows\System32\KernelBase.dll
859b2978	(3)	76e80	76f53	2	Mapped Exe	EXECUTE_WRITECOPY	\Windows\System32\kernel32.dll
877d66f0	(0)	77cb0	77deb	9	Mapped Exe	EXECUTE_WRITECOPY	\Windows\System32\ntdll.dll
8756d630	(2)	77ef0	77ef0	0	Mapped Exe	EXECUTE_WRITECOPY	\Windows\System32\apisetschema.dll
877de058	(3)	7f6f0	7f7ef	0	Mapped	READONLY	Pagefile-backed section
85a97078	(1)	7ffb0	7ffd2	0	Mapped	READONLY	Pagefile-backed section
86681b88	(2)	7ffd9	7ffd9	1	Private	READWRITE	
86185e28	(3)	7ffdf	7ffdf	1	Private	READWRITE	

Total VADs: 18 average level: 3 maximum depth: 4

```
kd> !pte 0
VA 00000000
PDE at C0600000 contains 0000000006E3E867 PTE at C0000000 contains 0000000000000000
pfn 6e3e ---DA--UWEV not valid
```

kd>

Invalid memory

Ln 0, Col 0 Sys 0:KdSrv:S Proc 000:0 Thrd 000:0 ASM OVR CAPS NUM

Mitigation Results

Function	Addr	Type	Protection	Result
NtAllocateVirtualMemory	1	MEM_RESERVE	READONLY	0xC0000018
NtAllocateVirtualMemory	1	MEM_COMMIT	READONLY	0xC0000018
NtMapViewOfSection	1	MEM_DOS_LIM*	READONLY	0xC0000018
NtProtectVirtualMemory	0		READWRITE	0xC000002D
NtProtectVirtualmemory	0		READONLY	0xC0000045
NtFreeVirtualMemory	0	MEM_RELEASE		0xC0000045

0xC0000018	STATUS_CONFLICTING_ADDRESSES
0xC000002D	STATUS_NOT_COMMITTED
0xC0000045	STATUS_INVALID_PAGE_PROTECTION

*Allows section mapping on page boundary on x86 platforms

Demo

- Null page mapping mitigation

Conclusion

Remarks and Conclusion

Future of the Win32k Subsystem

- **Win32k needs a much more consistent and security oriented design**
 - It should not be necessary for the kernel to make direct calls back into user-mode
 - Reconsider performance benefit of shared user and kernel-mode memory mappings
- **The Window Manager should provide mutual exclusion on a per-object basis**
 - Better suited towards multicore architectures
 - Similar to what is done in GDI and the NT executive

Conclusion

- **Legacy components constitute the most vulnerable parts of an operating system**
 - Security is not usually part of the original design
 - Win32k is built around very old GUI subsystem code
- **Kernel exploitation requires knowledge about the kernel address space**
 - Limiting access to such information is important
- **Although hard, mitigating Windows kernel exploitation is possible**

References

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 - mxatone (Uninformed Vol. 10)
- **Windows Creation Vulnerability (MS10-048)**
 - Nicolás Economou
- **Pointers and Handles: A Story of Unchecked Assumptions in the Windows Kernel**
 - Alex Ionescu
- **Understanding the Low Fragmentation Heap**
 - Chris Valasek

Questions ?

- Email: kernelpool@gmail.com
- Blog: <http://mista.nu/blog>
- Twitter: @kernelpool
- Norman MDT Blog:
<http://blogs.norman.com/category/malware-detection-team>